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India's ammonia industry: balancing growth with sustainability

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India, due to its agriculture-intensive economy, is a large consumer of nitrogen fertilisers. India's domestic ammonia manufacturing capacity is about 19 MMT today. The expansion of India's economy and the growing per capita income are likely to increase the demand for food grains, which, in turn, will increase the demand for ammonia. This study explores the growth of Indian ammonia production capacity on a decadal time scale, 2030–2070. The scope 1 and 2 emission intensities of India's ammonia production are estimated using a Life Cycle Assessment (LCA) approach under a business-as-usual (BAU) scenario. It is found that total emissions from ammonia manufacturing in India are likely to increase from 145 MMT in 2030 to about 540 MMT by 2070 without any abatement. Several technology interventions for emission reduction have been considered, and their impact on emission reduction has been estimated. These interventions are *in situ* carbon capture and utilization, alkaline water electrolysis (AWE), methane pyrolysis (MP), and energy decarbonisation. These interventions, when implemented, have the potential to significantly reduce emissions by 87% compared to the BAU scenario. The analysis points out the critical role of low-carbon intensity hydrogen, carbon capture technologies, and the availability of renewable energy. The analysis presented in this study provides valuable insights to both policymakers and industry stakeholders and develop a roadmap to mitigate the negative impacts of GHG emissions and promote the sustainable growth of the ammonia manufacturing industry in India.

Sustainability spotlight

This study highlights the critical need to decarbonize ammonia production in India. India's ammonia production is likely to grow by at least fourfold between now and 2070. This has the potential to increase its share of GHGs from this sector of the manufacturing economy. Therefore, India must focus on decarbonizing ammonia production through multiple technological interventions. This approach directly aligns with the UN Sustainable Development Goals (SDGs), including Goal 7 (Affordable and Clean Energy), Goal 9 (Industry, Innovation, and Infrastructure), and Goal 13 (Climate Action). By advocating sustainable agricultural inputs, the study contributes to Goal 2 (Zero Hunger). It fosters global efforts toward net-zero emissions by 2070, supporting inclusive and sustainable industrial growth while combating climate change for a resilient future. Apart from SDGs, this study also provides the roadmap to fulfill India's commitment to achieving net zero emissions by 2070, declared at the United Nations Climate Change Conference in Glasgow Summit (COP26) in 2021.

1 Introduction

Ammonia has had a profound global impact since the discovery of its synthesis from hydrogen and nitrogen by Haber and Bosch in Germany at the beginning of the 20th century.[1] Current global ammonia production is about 176 MMT per year.[2] It is predominantly produced by steam methane reforming (SMR), or coal-derived, accounting for 80% (approximately 147 MMT in 2020) and 20% (about 38 MMT in 2020), respectively.[3] Ammonia is the basic feedstock for inorganic fertilizers (70% of production) that currently supports food production for around half of the world's population.[4,5] The remaining ammonia is used as a chemical feedstock (30%) in industrial applications, including explosives for mining and construction, plastics, cleaning products, and textiles.[4,5] India is the third-largest producer of ammonia, accounting for ~8% of global production.[5,6] Thus, India's ammonia industry must be examined within this global context, as the demand, consumption and production of ammonia are projected to increase exponentially during the next three to five decades as the Indian economy is hugely dependent on agriculture.[7,8] Agriculture contributes approximately ~15% to India's GDP today and is expected to be about 5% of the projected GDP by 2050.[9] A growing population and rising income levels will increase food

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consumption, resulting in a large demand for nitrogen in the soil. Therefore, ammonia consumption is likely to increase from 19 MMT to about 45 MMT in 2050 based on the estimated population of 1.7 billion and grain requirement of 580 MMT.[7]

Apart from being the most critical chemical, ammonia production is a highly energy-intensive process, consuming around 1.8% of global energy output each year (SMR accounts for over 80% of the energy required) and emitting about 500 MMT of CO_2 (about 1.8% of global CO_2 emissions).[5,10] Ammonia synthesis is presumably the most significant CO_2-emitting process in the chemical industry.[4] Along with cement, steel and ethylene production, it is one of the 'big four' industrial processes where a decarbonization plan must be developed and implemented to meet the net zero carbon emission targets by 2050.[11] At around 2.4-ton CO_2 eq. tons per ton of production, it is nearly twice as intensive as crude steel production and four times that of cement, on a direct CO_2 emission basis.[5] Direct emissions from ammonia production currently amount to 450 MMT CO_2, whereas indirect CO_2 emissions are around 170 MMT CO_2 per year and stem from two primary sources – electricity generation and the chemical reaction when urea-based fertilizers are applied to soil.[5] Without mitigation efforts, these emissions could substantially increase by 2050.[5] In the Stated Policies Scenario (Business as Usual-BAU), ammonia production will increase by nearly 40% by 2050, driven by economic and population growth. CO_2 emissions will grow by 3% by 2030 before exponentially increasing if technology interventions and energy decarbonization are not implemented.[5,11] India emitted around 45 MMT of CO_2 in 2022 based on ammonia production in that year.[5,11]

Life Cycle Assessment (LCA) is an invaluable tool for accurately calculating emissions from production processes. By offering a systematic framework to evaluate inputs, outputs, and potential environmental impacts, LCA allows for a comprehensive analysis across various ecological impact categories throughout a product's life cycle.[12] Previous studies have leveraged LCA to analyze ammonia production methods. For instance, comparisons have been made between nuclear and coal-based electrolysis processes[13,14] and among production methods using hydropower, nuclear energy, biomass, and municipal waste.[15] However, these studies focus on specific technologies rather than providing a holistic perspective on country-specific impacts. Only a few studies have explored the impact categories within the planetary boundaries. For example, one study investigated the low-carbon Haber–Bosch process, incorporating technologies such as steam methane reforming (SMR), carbon capture and utilization, alkaline electrolysis, and proton exchange membranes. While this research provided valuable insights, it lacked a focus on region-specific emission intensities and production scales.[12]

Country-specific LCA-based studies are limited. In Spain, researchers assessed the environmental and economic feasibility of low-carbon intensity ammonia production using renewable energy, integrating LCA with techno-economic analysis (TEA). This study highlighted the role of renewables, natural gas costs and carbon pricing in advancing sustainable ammonia production. However, the study did not consider Spain's production capacity.[16] Similarly, a study in Algeria evaluated sustainable ammonia production technologies compared to global benchmarks.[17] Another study in China examined the interplay between greenhouse gas emissions and the disruptive potential of ammonia synthesis technologies on Earth's nitrogen cycle.[18] To the best of our knowledge, no study comprehensively evaluates emissions from ammonia production in the context of a country's medium to long-term growth.

Therefore, there exists an urgent need to examine the emission intensity of India's ammonia production and address the potential impact of abatement technologies using an LCA and impact analysis approach. Furthermore, the study evaluates the current emission levels by identifying the emission sources based on the technology practised in India. The framework categorizes CO_2 emissions into scope 1 and scope 2, including direct CO_2 emissions (process emissions) and indirect CO_2 emissions from the manufacturing process. Furthermore, we attempt to formulate a roadmap for decarbonization on a decadal timescale from the present to 2070. This study also seeks to understand the relevance of potential abatement technology interventions and their impact on the Indian ammonia industry.

2 Methodology

The ammonia production data were collected from the literature. The system boundary and the process inventory data were validated in consultation with Deepak Fertilizers and Petrochemicals, Taloja, India. We studied the growth trajectory of ammonia production and consumption to extract insights about its historical and projected growth trajectory from the present to 2070. The process steps involved in ammonia production (Haber–Bosch process) were mapped based on data available in the literature. Furthermore, the study examines four technology interventions, namely, (1) the effect of CO_2 capture; (2) the integration of Alkaline Water Electrolyzer (AWE) for low-carbon-intensity hydrogen production; (3) methane pyrolysis (MP) as an alternative low-carbon hydrogen production pathway; and (4) energy decarbonization by integration of renewable energy (RE) into the grid. We initially evaluated these scenarios as per BAU because the manufacturing plants are already in commercial operation. Building upon the insights gained from the ammonia production process, the Life Cycle Assessment (LCA) methodology's objectives and scope were formulated, adhering to the guidelines outlined in ISO 14040 and 14044. During this phase, the system boundary for the study is defined, and the environmental, resource, and human impacts associated with the ammonia production process are quantified based on the current industrial practices in India. This involves assessing and characterizing all resource flows under scope 1 & 2 emissions through Life Cycle Inventory (LCI) analysis. Based on such an analysis, emissions for a baseline case (2020) as well as the decadal emissions till 2070 were computed using Business-as-Usual (BAU) and abatement scenarios (AS) by formulating technology interventions for decarbonization. To ensure transparency in emission reporting, three metrics are used in this study. Annual emissions represent total emissions for a specific year which is calculated by multiplying annual ammonia production with emission intensity of that specific year. Decadal aggregated emissions refer to the sum of annual emissions over each 10 year window (*e.g.*, 2020–2029 = 10 years, both the start and end years inclusive; the final window 2060–2070 spans 11 years). Cumulative emissions represent the total emissions over the entire modelling period (2020–2070), obtained by summing all annual values from 2020 to 2070 inclusive (SI 2). To assess uncertainty, a Monte Carlo simulation was performed in SimaPro v.9.5.0.2 using the Impact 2002+ (V2.15) method to evaluate variability in the climate change damage indicator and to compare robustness across production pathways. The simulation was run for 1000 iterations with a 95% confidence interval. A normal distribution with a fixed geometric standard deviation of 5% was applied to foreground parameters. Uncertainty in background processes was propagated automatically using the pedigree matrix uncertainty values embedded in the Ecoinvent v3.4 database, which assigns lognormal distributions to background inventory flows based on data quality indicators. The simulation was performed separately for each production pathway *i.e.*, conventional SMR, SMR with CCU and RE (2070), AWE with CCU and RE (2070), and methane pyrolysis with CCU and RE (2070). No cross-parameter correlations were assumed, and all foreground and background parameters were treated as statistically independent across iterations, consistent with the default SimaPro Monte Carlo framework.

2.1 Production process

An ammonia manufacturing process is highly integrated and can be divided into four functional stages: hydrogen production from methane *via* steam methane reforming (SMR), nitrogen extraction from air, ammonia synthesis through the Haber–Bosch process, and the final conversion of ammonia gas into its liquid form.[19] We have considered three cases: (1) conventional SMR, wherein the reaction is mostly allothermic; (2) the SMR + ATR case, wherein the reaction is autothermic; and (3) the SMR/air case, wherein an additional unit is present to separate nitrogen from air. A detailed representation of the process is shown in Fig. 1.

2.1.1 Stage 1: hydrogen production *via* SMR. Hydrogen is produced through SMR, involving primary and secondary reactors operating at high temperatures and pressure.[20] The process includes water–gas shift reactions, CO_2 removal, and methanation, with significant waste heat recovery for steam generation and compression energy (Fig. S1). The first SMR reactor operates under allothermal conditions at around 850–900 °C and 25–35 bar, and the energy required for the endothermic reaction is provided by external combustion of methane fuel through furnace tubes that run through the catalyst bed.[20,21] The second SMR reactor is autothermal; air is compressed and fed to the reactor to provide heat of reaction by partial oxidation of the reagents at 900–1000 °C.[20,21] The addition of air also provides the stoichiometric nitrogen required for the downstream Haber–Bosch reaction. The SMR process exports steam to be used elsewhere, mostly for compression energy.[20] The SMR outlet mixture of carbon monoxide, hydrogen, and unreacted steam and methane is introduced into the two-stage water–gas shift (WGS) reactor to maximise CO conversion to hydrogen. The WGS reaction is exothermic, and heat must be removed to minimise CO concentration at equilibrium. Although the SMR reactions are endothermic, the high reaction temperature and the need to cool the gas substantially for the water gas shift reaction mean that there is substantial waste heat available. This heat is used for generating high-pressure steam, which is expanded in steam turbines for compression, mainly used for compression of the feed in the Haber–Bosch loop and the reformer combustion air compressor, which are the largest two energy users.[20,21] The use of methane as a feedstock inevitably leads to significant CO_2 emissions from the process, and this is further compounded by the use of methane as fuel for the primary reformer furnace.

We have considered two conditions wherein, in the first case, the reactor operates under allothermal conditions where the energy required for the endothermic reaction is provided by external combustion of methane fuel through furnace tubes that run through the catalyst bed.[21] The second case is SMR + ATR, wherein the reaction is autothermal. The air is compressed and fed to the reactor to provide heat of reaction by partial oxidation of the reagents at 900–1000 °C. The addition of air also provides the stoichiometric nitrogen required for the downstream Haber–Bosch reaction.

2.1.2 Stage 2-nitrogen production (only in the case of SMR/air). Nitrogen is separated from air using cryogenic processes, operating at approximately −170 to −196 °C (near the boiling points of liquid nitrogen [−196 °C] and liquid oxygen [−183 °C]), with oxygen as a by-product[19] (Fig. S2).

2.1.3 Stage 3-ammonia synthesis (Haber–Bosch). Ammonia is synthesized through the Haber–Bosch process *via* the catalytic reaction between hydrogen and nitrogen ($N_2 + 3H_2 \rightleftharpoons 2NH_3$). The reaction is carried out over a heterogeneous iron-based catalyst under elevated temperature and pressure conditions to achieve practical conversion rates. Industrial catalysts typically consist of magnetite-derived iron promoted with potassium, alumina, and calcium oxides, which enhance catalytic activity, structural stability, and resistance to sintering.

The catalytic mechanism involves the adsorption of nitrogen and hydrogen onto the catalyst surface. Activation of nitrogen is the rate-limiting step due to the strong N≡N triple bond. The iron catalyst facilitates dissociation of molecular nitrogen into atomic nitrogen, which subsequently undergoes stepwise hydrogenation, forming surface intermediates (NH and NH_2) before desorbing as ammonia. Promoters improve the electron density at the catalyst surface, thereby enhancing nitrogen dissociation and overall reaction kinetics.

From a thermodynamic perspective, ammonia synthesis is an exothermic reaction favoured at high pressure because the number of gas molecules decreases during ammonia formation. However, lower temperatures would favour equilibrium conversion but result in slow reaction rates due to kinetic limitations associated with nitrogen activation. Industrial operation, therefore, represents a compromise between thermodynamic equilibrium and reaction kinetics, typically

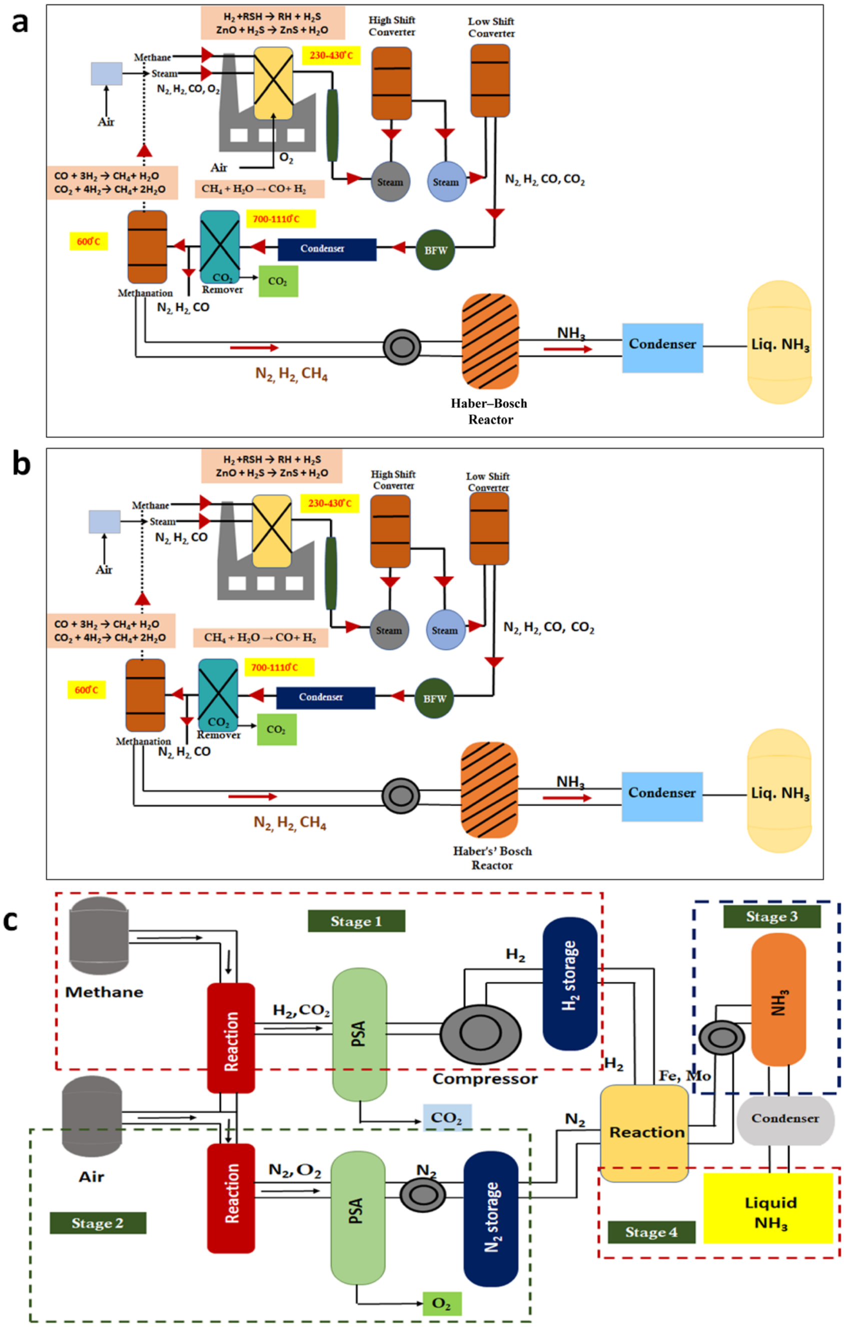

Fig. 1 Process flow diagrams representing three industrial configurations of ammonia production considered in this study: (a) conventional steam methane reforming (SMR), (b) SMR integrated with autothermal reforming (SMR + ATR), and (c) SMR with a separate nitrogen production unit (SMR/air). The diagrams illustrate hydrogen generation, nitrogen supply pathways, ammonia synthesis *via* the Haber–Bosch process, and downstream liquefaction. These configurations are the basis for the comparative life cycle assessment under the BAU and abatement scenarios.

operating at temperatures of 400–500 °C and pressures between 10–30 MPa. These operating conditions significantly influence energy demand, compression requirements, and overall environmental impacts, making the Haber–Bosch stage a critical hotspot in ammonia production lifecycle assessments.

2.1.4 Stage 4-liquid ammonia production. The cryogenic process is used to transform the gaseous ammonia into liquid ammonia. This is also an energy-intensive process, mainly emitting vast amounts of steam as a by-product[19] (Fig. 1).

2.2 System boundaries

Based on the process parameters, the system boundary was designed using the inputs and the primary outputs from the process (Tables S1–S5). The separate system boundaries of each stage are provided in SI 1 (Fig. S3–S5). The overall system

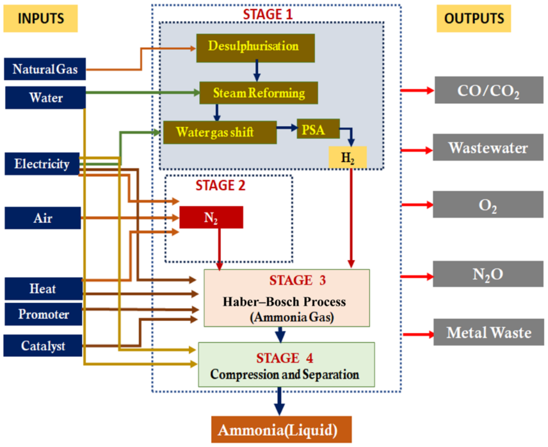

Fig. 2 Cradle-to-gate system boundary for liq. ammonia production. This collectively incorporates stage 1, stage 2, stage 3 and stage 4 inputs for the major output, liquid ammonia. *Note: stage 2 is only present in the case of SMR/air.

boundary for the typical ammonia industry is represented in Fig. 2.

2.3 Life cycle assessment (LCA)

The environmental sustainability of the ammonia industry was thoroughly assessed in compliance with ISO 14040:2006 standards using SimaPro v.9.5.0.2 software.[22] This study employs a cradle-to-gate system boundary with a functional unit of 1 ton of ammonia as an output. Initial framework details of ammonia production within the foreground system boundary were obtained based on Indian industrial conditions. The Life Cycle Impact Assessment (LCIA) utilized the Impact 2002+ (V2.15) methodology to evaluate sustainability across four end-points and fifteen middle categories.[22,23] Direct inputs, such as raw materials, chemicals, and energy, along with outputs, including targeted products, by-products, and environmental effluents at each process step, were drawn from the Ecoinvent v3.4 database in SimaPro v.9.5.0.2. The ‘Allocation at the point of substitution’ (APOS) system model version of the database, based on an attributional approach, was employed to ensure accurate assessment and allocation of environmental impacts throughout the ammonia production life cycle.

3 Results and discussion

3.1 Indian ammonia market and projections

We examined the ammonia production capacity in India from 2010 to 2021 and its correlation with India's historical GDP growth (Fig. S6). Based on this, the future ammonia consumption was forecast for 2070 (Fig. 3). This plot shows a linear increase in production with a reasonable correlation coefficient. This indicates that GDP can be used as a metric to predict the growth of the Indian ammonia industry. The plot shown in Fig. S7 was extrapolated using forecasted GDP growth as projected by the IMF[24] (International Monetary Fund). The estimated future capacity growth follows a linear regression equation leading to a projected ammonia production of 77 MMT by 2070, with decadal production estimates of 21, 30, 40, and 56 MMT for 2030, 2040, 2050 and 2060, respectively. This projection indicates that India will be among the leading ammonia producers by 2070 (Fig. 3).

The major players in ammonia production are Indian Farmers Fertilizer Cooperative Limited (IFFCO), Chambal Fertilizers and Chemicals Limited, Krishak Bharati Cooperative Limited (KRIBHCO), Rashtriya Chemicals & Fertilizers Limited (RCF), and Deepak Fertilizers and Petrochemicals[25] (Fig. S8 and Table S6). While most of the plants operate with natural gas as a feedstock, the plants located in Sindri, Talcher, and Lakhanpur are based on coal.[25] Interestingly, the Nangal ammonia plant in Punjab, India, commissioned in 1963, was originally powered by hydroelectricity from the Bhakra–Nangal Dam and hydrogen generated by electrolysis.[26] India's grain production in 2021–22 was 315.72 MMT, and the fertilizer requirement for the same year was 34 MMT[7,8] (Fig. S9). Using the per-capita grain consumption in 2021–22 as the base, we estimate that India's grain production will reach as high as 580 MMT to feed a population of 1.7 billion by 2050.[27] This could translate into an ammonia requirement of 48 MMT by 2050, which is in line with the projections of the IARI.[9] This value is marginally higher than what the projections based on GDP indicate (Fig. 3).

3.2 CO_2 emissions under the BAU scenario

3.2.1 Scenario 1: the commercial Haber–Bosch process with SMR. Our study estimates the share of emissions of ammonia production in India to be 7.02 CO_2 eq. tons per ton of liq. ammonia in 2024, assuming a grid mix of 78% to 22% (fossil to RE, Fig. S10 and S11).[28] Based on the projected increase in ammonia production and LCA, it is anticipated that the CO_2 eq. emissions will be 145, 201, 279, 389 and 540 MMT for years 2030, 2040, 2050, 2060 and 2070, respectively. This is based on the assumption that technology will remain more or less the same between now and 2070. The anticipated growth in emissions from 2010 to 2070 is shown in Fig. S10 for the BAU

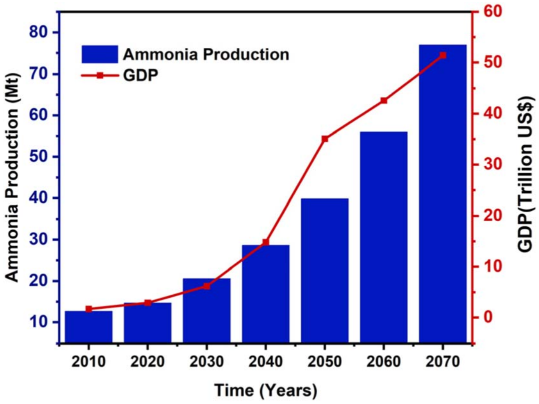

Fig. 3 Relationship between India's GDP and ammonia production capacity (2010–2021), along with projected production up to 2070 based on IMF GDP forecasts. The linear regression demonstrates a strong positive correlation between economic growth and ammonia production, supporting the use of GDP as a proxy indicator for long-term ammonia demand and capacity expansion.

scenario. Under the BAU scenario, the cumulative CO_2 emissions by the year 2070 are projected to reach a staggering 13.6 GT in the absence of any mitigation strategies. On a decadal scale, the aggregated emissions are estimated to be 1207 MMT for 2020–2029, 1684 MMT for 2030–2039, 2342 MMT for 2040–2049, 3256 MMT for 2050–2059, and 5067 MMT for 2060–2070, culminating in a total cumulative emission of 13.6 GT over the full modelling period (2020–2070) (SI 2; Table S7 SI).

3.2.2 Scenario 2: the commercial Haber–Bosch process with SMR and ATR. In the case of an autothermal reactor (ATR), heat is generated by partially burning natural gas to drive the steam methane reforming (SMR) reaction. While this method is more efficient in terms of heat recovery, it requires an additional supply of pure oxygen, making the process more energy-intensive. Our study estimates the share of emissions of ammonia production in India to be 7.55 CO_2 eq. tons per ton of liq. ammonia in 2024, assuming a grid mix of 78% to 22% (fossil to RE, Fig. S12).[28] Based on the projected increase in ammonia production and LCA, it is anticipated that the CO_2 eq. emissions will be 155, 216, 301, 432 and 581 MMT for the years 2030, 2040, 2050, 2060 and 2070, respectively. This is based on the assumption that technology will remain more or less the same between now and 2070. Under the BAU scenario, the cumulative CO_2 emissions by the year 2070 are projected to reach a staggering 14.5 GT in the absence of any mitigation strategies. On a decadal scale, the aggregated emissions are estimated to be 1298 MMT for 2020–2029, 1812 MMT for 2030–2039, 2519 MMT for 2040–2049, 3502 MMT for 2050–2059, and 5450 MMT for 2060–2070, culminating in a total cumulative emission of 14.6 GT over the full modelling period (2020–2070) (SI 2; Table S7 SI).

3.2.3 Scenario 3: the commercial Haber–Bosch process with SMR and the N_2 production unit. Some plants integrate N_2 production as part of the process alongside SMR, often referred to as the SMR/air configuration. This approach requires additional energy to separate nitrogen, oxygen, and trace gases from the air. Our study estimates the share of emissions of ammonia production in India to be 7.57 CO_2 eq. tons per ton of liq. ammonia in 2024, assuming a grid mix of 78% to 22% (fossil to RE, Fig. S13 and S14).[28] This process emits a more or less similar amount of CO_2 as SMR + ATR. Based on the projected increase in ammonia production and LCA, it is anticipated that the CO_2 eq. emissions will be 156, 218, 301, 419 and 582 MMT for the years 2030, 2040, 2050, 2060 and 2070, respectively. This is based on the assumption that technology will remain more or less the same between now and 2070. Under the BAU scenario, the cumulative CO_2 emissions by the year 2070 are projected to reach a staggering 14.6 GT in the absence of any mitigation strategies. On a decadal scale, the aggregated emissions are estimated to be 1301 MMT for 2020–2029, 1816 MMT for 2030–2039, 2525 MMT for 2040–2049, 3511 MMT for 2050–2059, and 5464 MMT for 2060–2070, culminating in a total cumulative emission of 14.6 GT over the full modelling period (2020–2070) (SI 2; Table S7 S1). These figures highlight an alarming trajectory of increasing emissions, emphasizing the critical need for implementing effective mitigation measures. Comparative CO_2 emissions from SMR, SMR/air and SMR + ATR are illustrated in Fig. 5a.

3.2.4 Scenario 4: the Haber–Bosch process using *in situ* carbon capture and utilization. An effective strategy to mitigate emissions in the ammonia production process is the integration of carbon capture and utilization (CCU) technology with natural gas-based production, specifically the SMR process.[12,19] By incorporating CCU technology (40% as in 2024), which captures a significant percentage of carbon emissions directly from the production process, our analysis under scenario 1 demonstrated a reduction in emissions. The findings indicate that emissions decreased to 6.8 CO_2-eq. tons per ton of liquid ammonia produced (Fig. S15). This represents a reduction of approximately 3% compared to the baseline, as the emissions mostly come from the use of electricity. At present, about 40% of the CO_2 emitted by weight during SMR is being captured (in 2024, assuming a grid mix of 78% to 22% (fossil to RE)). In this study, CCU is applied to process CO_2 streams generated during SMR and water–gas shift reactions, which represent the highest concentration CO_2 sources in ammonia production. The capture rate is defined as the fraction of process CO_2 captured relative to the total process CO_2 generated. A baseline capture rate of 40% was assumed for 2024 based on current industrial practice, with progressive increases across future scenarios. The CCU system boundary includes CO_2 capture and compression, while downstream transport and geological storage are excluded from our study since it focuses mainly on the cradle-to-gate system. Scope-wise emission intensities derived from SimaPro indicate that CCU primarily reduces scope 1 emissions associated with process CO_2 streams, whereas scope 2 emissions remain comparatively stable due to additional energy demand for capture and compression. Consequently, the net reduction observed in the CCU scenario is modest, as combustion-related emissions remain outside the capture boundary. Two distinct CCU boundaries are applied in this study. (1) In Section 3.2.4, scenario 4, the process-stream CCU is considered where capture is applied exclusively to high-concentration CO_2 streams from SMR and water–gas shift reactions (CO_2 concentration 15–30%). The reformer flue gas (combustion exhaust, ~8–12% CO_2) is not considered for capture in this analysis. Therefore, captured CO_2 is only a fraction of the total emitted CO_2. The energy penalty is limited to capture and compression of process stream from the SMR and WGS reactions. (2) Section 3.3.4 describes future plant-level CCU where capture systems are progressively retrofitted to cover all the emission streams including reformer flue gas, with capture rates rising from 50% (2030) to 100% (2070) of total plant CO_2. This represents a future state consistent with India's emerging CCU policy framework.

On the assumption that CO_2 capture will increase by 50%, 60%, 70%, 80% and 100% for the years 2030, 2040, 2050, 2060 and 2070, respectively. Incorporating CCU in SMR technology, the amount of CO_2 emissions will reduce by 11.6% by 2070 (with the current energy mix) (Table S8). These results underscore the significance of carbon capture and utilization technology as a pivotal intervention in advancing low-carbon ammonia production. But, even at high capture levels, residual scope 1

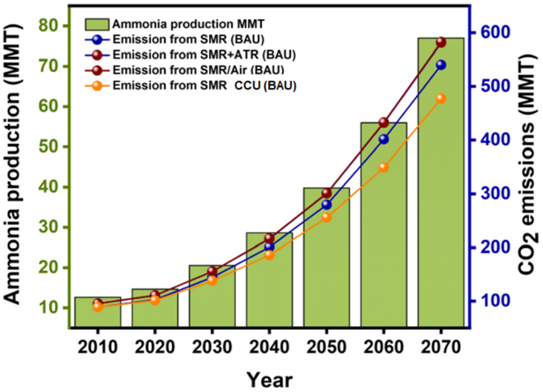

Fig. 4 Projected annual CO_2 emissions (MMT) from India's ammonia sector from 2030 to 2070 under the Business-as-Usual (BAU) scenario and with incremental technology interventions. The figure illustrates the steep growth trajectory of emissions in the absence of decarbonization and highlights the relative mitigation impact of carbon capture and utilization, renewable energy integration, and low-carbon hydrogen pathways.

emissions persist due to uncaptured combustion-related flue-gas streams (Fig. 4).

3.3 Technology interventions for CO_2 emission reduction

Any reduction in emissions beyond the level of 6.88 CO_2 eq. tons per ton of liq. ammonia production (achieved by deploying CCU technologies) will require additional technology interventions, which are discussed below. We have examined all the available technologies at various stages of development and their readiness levels for deployment between now and 2070 (Table 1). In instances where specific information for India was lacking, we used globally available information.

3.3.1 Alkaline Water Electrolysis (AWE). Alkaline Water Electrolysis (AWE) produces H_2 from water using an alkaline electrolyte solution[29] (SI). Our study indicates that scope 2 CO_2 emissions increased when the AWE process was included due to the high energy intensity of the electrolysis process (56 kWh kg^{-1} H_2 (ref. 29 and 30)). We conclude that the inclusion of the electrolysis process is beneficial from the standpoint of reducing emissions (5.63 CO_2 eq. tons per ton of liq. NH_3 using H_2 from an electrolyzer (Fig. S16 and S17) *vs.* 7.02 CO_2 eq. tons per ton of liq. NH_3 using SMR).

The high energy intensity electrolysis process (56 kWh kg^{-1} H_2,[29,30] scope 2 emissions) using an energy mix of 78 : 22% (fossil: RE) does not confer any significant benefit to the ammonia production process from the point of view of reducing emissions. However, an AWE using an energy mix of 13 : 87% (fossil: captive RE) could reduce the emissions to as low as 0.69 CO_2 eq. tons per ton of liq. NH_3. It is also anticipated that the efficiency of an AWE will improve in the future. On the assumption that the energy intensity of an AWE will be approximately 45 kWh kg^{-1} of H_2 by 2040 (assuming an energy mix of 44 : 56% fossil: RE) and 41 kWh by 2060 (assuming an energy mix of 24 : 76% fossil: RE), we estimate that the emissions could reduce to 2.73 CO_2 eq. tons per ton of liq. NH_3 and 0.92 CO_2 eq. tons per ton of liq. NH_3 by 2040 and 2060, respectively (Fig. S24). Furthermore, we have assumed that 50 wt% of H_2 will be produced from an AWE and the balance from other technologies by 2070.

Today, companies such as AM Green and Acme Group are making significant strides toward low-carbon intensity ammonia production in India. AM Green, along with John Cockerill, has announced a 1.3 GW AWE facility. This electrolyzer will support 1 MMT per annum of ammonia production in Kakinada, Andhra Pradesh. Additionally, AM Green is developing other green ammonia plants across the country, including a 1.0 MMT per annum facility in Tuticorin, Tamil Nadu, a 1.5 MMT per annum plant in Kandla, Gujarat, and a smaller 0.1 MMT per annum plant in Una, Himachal Pradesh.[31]

Similarly, Acme Group has commissioned a plant in Bikaner, Rajasthan, which began production in November 2021. This facility utilizes 10 MW of solar photovoltaic (PV) capacity and 5 MW of AWE capacity to produce hydrogen, enabling an annual production of approximately 1.5 MMT of ammonia.[32] The group has also announced a 1.5 GW electrolyzer with a 5 GW solar power plant to produce 1.1 MMT of ammonia.[33] These early initiatives underscore India's growing commitment to renewable energy and sustainable ammonia production.

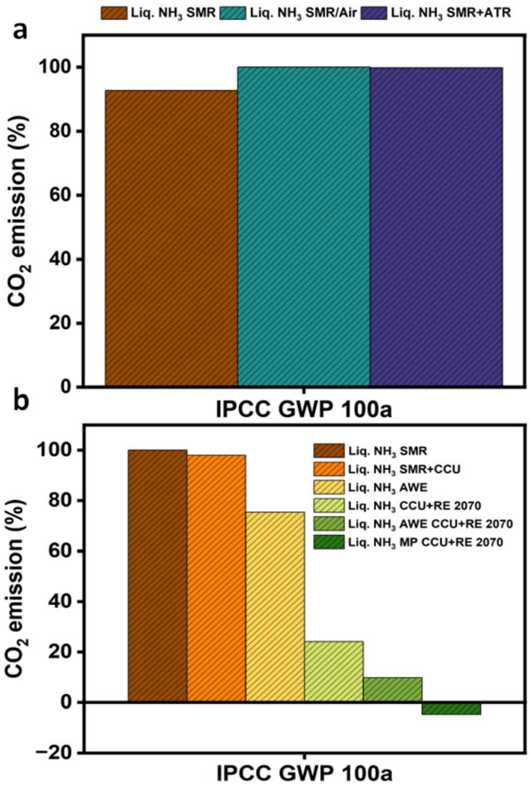

Fig. 5 (a) Comparative CO_2 emission intensities (tons CO_2 eq. per ton of NH_3) for the three industrial configurations: SMR, SMR + ATR, and SMR/air under the current grid mix. (b) Reduction in emission intensity achieved through progressive integration of CCU and renewable energy (RE) between 2030 and 2070. The figure highlights the dominant influence of grid decarbonisation and CCU in lowering scope 1 and scope 2 emissions.

Table 1 Process intervention on a decadal-scale with its share and TRL level

		Year					
S. no.	Technology	2020	2030	2040	2050	2060	2070
1	SMR	**% Share**[a]					
		<95	90	80	65	50	30
		TRL					
		9	9	9	9	9	9
2	SMR with CCU	**% Share**					
		40	50	60	70	80 (ref. 36)	100 (ref. 37)
		TRL					
		8–9	8–9	8–9	8–9	8–9	8–9
3	Hydrogen from AWE	**% Share**					
		>5	10	20	35	40	50
		TRL					
		7–8	8–9	8–9	8–9	8–9	8–9
		Energy efficiency of AWE (kWh)					
		56	56	45	45	41	41
4	Methane pyrolysis	**% Share**					
		0	0	0	0	10	20
		TRL					
		2–3	3–4	4–5	6–7	7–8	8–9
5	Renewable energy (RE share % in the primary energy mix)	22 (ref. 28)	50 (ref. 38)	58[a]	66[a]	76[a]	87[a]

[a] All projections were done based on the reported CAGR of IEEFA, India's Renewable Energy Journey: Short-Term Hiccups but Long-Term Trajectory Intact[28] and NITI Aayog, Carbon Capture, Utilisation and Storage (CCUS): Policy Framework and Its Deployment Mechanism.[38]

3.3.2 Methane pyrolysis. Methane pyrolysis (MP), represents an alternative way of producing hydrogen without emissions of GHGs.[34] This process is typically conducted at high temperature and in the presence of suitable catalysts. While this process holds significant promise to reduce the carbon intensity of hydrogen, inadequate demand for the co-product carbon generated by large-scale methane pyrolysis plants appears to be a barrier to adoption of this technology. Stoichiometrically, 1 ton of H_2 will generate 3 tons of carbon.[35] In the current study, we have assumed 100% carbon (co-product) utilization. Therefore, hydrogen produced by the MP process will produce a net carbon negative emission of −3.17 CO_2 eq. tons per ton of H_2 by 2070, whereas hydrogen production under the BAU scenario (current practices) with MP will result in emissions of 1.73 CO_2 eq. tons per ton of H_2 (Fig. S18, S19, S26 and S27). The lower emissions in MP are attributed to the carbon production, which is credited to the system. To rigorously assess the sensitivity of the net-negative emission claim to carbon utilization, stoichiometric yield of methane pyrolysis was held constant, such that the production of 1 ton of hydrogen is inherently coupled with the generation of approximately 3 tons of carbon. The analysis varied the extent to which the co-produced carbon is assumed to be utilized and credited for displacement, thereby isolating the effect of co-product allocation on the overall life cycle emissions. Three allocation scenarios were considered to understand the full spectrum of practical possibilities: (i) 0% utilization, where the solid carbon is not utilized and therefore receives no environmental credit; (ii) 50% utilization, representing a partial market uptake of the co-product; and (iii) 100% utilization, corresponding to complete displacement of conventional carbon in applications and maximum credit assignment. As the fraction of carbon credited for displacement increases, the magnitude of avoided emissions increases proportionally. This directly translates into a progressive reduction in the net emission intensity of the methane pyrolysis pathway, highlighting the critical role of co-product utilization in determining the overall sustainability performance. Under conditions where complete utilization occurs (100%), the system achieves net-negative emissions of −3.17 CO_2 eq. tons per ton of H_2, demonstrating the maximum climate benefit. When utilization is reduced to 50%, emissions increase to 0.15 CO_2 eq. tons per ton of H_2, reflecting partial loss of displacement credit. In the absence of any carbon utilization (0%), emissions further increase to 3.56 CO_2 eq. tons per ton of H_2, indicating that the environmental consequences of this technology are strongly dependent on effective co-product utilization (Fig. S27).

However, the technology remains at a lower technology readiness level compared to SMR and AWE, and large-scale industrial deployment is still some time away. Key feasibility challenges include reactor scale-up, handling and valorisation of solid carbon, and long-term operational stability. Economic viability depends on the carbon market value and process energy requirements. Policy support for emerging hydrogen technologies will influence the potential for quick adoption.

3.3.3 Energy decarbonization. The average specific energy consumption of an Indian ammonia plant is 34.3 GJ per ton compared to the world average of 41 GJ per ton.[4,36] With an increasing proportion of RE in the grid, emissions can further decrease. For this assessment, we assume that RE is exclusively sourced from solar energy. Critical units of the ammonia process will still run on grid power even with a renewable energy mix, as captive power is required as a backup power source. In

2024, the energy mix was considered to be 78% fossil and 22% RE;[28] by 2070, the ratio is assumed to be 13% to 87%, respectively (Fig. 5b and Table 2).

3.3.4 Energy decarbonization with carbon capture and utilization. Net CO_2 emissions in the abatement scenario were calculated based on the assumed share of fossil: renewable energy flowing into the grid along with the CCU percentage (Fig. S20–S26). Incorporating the energy mix and CCU share (Table 1), it was estimated that 4.4 CO_2 eq. tons per ton of liq. NH_3 in 2030, 3.8 CO_2 eq. tons per ton of liq. NH_3, 3.2 CO_2 eq. tons per ton of liq. NH_3, 2.5 CO_2 eq. tons per ton of liq. NH_3 and 1.7 CO_2 eq. tons per ton liq. NH_3 will be emitted. This suggests that by incorporating only renewable energy and CCU technology, a significant reduction of 75% by 2070 (from a baseline of 6.8 CO_2 eq. tons per ton of liq. NH_3) can be achieved (Fig. 5b). The CCU approach considered in this study differs from the conventional *in situ* carbon capture and utilization integrated within the Haber–Bosch process. In traditional ammonia plants, a portion of the process CO_2 generated during SMR and water–gas shift reactions is captured and directly utilized. In contrast, the CCU framework evaluated here represents a broader plant-level implementation of carbon capture systems applied to major emission streams, including process CO_2 and reformer flue gases. The captured CO_2 may then be directed toward external utilization pathways such as chemical synthesis, fuel production, or long-term geological storage. This broader deployment is largely driven by national decarbonization policies and long-term industrial transition strategies, particularly those outlined under India's emerging CCUS policy framework.[37–39] Consequently, unlike *in situ* CO_2 reuse within the ammonia synthesis loop, this CCU strategy aims to reduce overall lifecycle emissions by integrating capture technologies across the production chain and enabling downstream carbon utilization options beyond the ammonia facility. While the above interventions represent near- and medium-term decarbonization strategies with clear industrial feasibility, emerging research is exploring alternative low-temperature ammonia synthesis pathways that may shape the long-term future of sustainable ammonia production.

3.3.5 Emerging sustainable ammonia synthesis pathways. In addition to the thermochemical Haber–Bosch process, recent research has focused on photo- and electro-catalytic nitrogen reduction reactions (NRRs) for ammonia synthesis under ambient/near-ambient conditions. Such approaches have attracted considerable attention since they show potential for improved sustainability of the ammonia synthesis process. Several excellent studies are extant in the literature that describes such processes.[40–49] In photocatalytic nitrogen reduction, semiconductor or hybrid photoactive materials absorb solar energy to generate electron–hole pairs; photogenerated electrons reduce adsorbed N_2 species to NH_3, while holes oxidize water or sacrificial donors.[50] In electrocatalytic nitrogen reduction reactions (NRRs), renewable electricity is used to drive the activation and stepwise proton–electron transfer reduction of molecular nitrogen at the cathode, typically in aqueous or non-aqueous electrolyte systems.[47] Concurrently, water oxidation occurs at the anode to complete the electrochemical circuit. The targeted cathodic reaction involves the six-electron reduction of N_2 to NH_3 ($N_2 + 6H^+ + 6e^- \rightarrow 2NH_3$ in acidic media or the corresponding OH^- mediated pathway under alkaline conditions). However, practical implementation remains challenging due to the strong N≡N triple bond, low nitrogen solubility in aqueous electrolytes, sluggish reaction kinetics, and the competitive hydrogen evolution reaction (HER), which often dominates under similar potentials and reduces faradaic efficiency for ammonia formation.[50,51]

Recent catalyst engineering strategies have significantly advanced the field. Defect-engineered materials, single-atom catalysts, porous coordination polymers, and metal–organic frameworks have been developed to stabilize activated N_2 intermediates and enhance adsorption strength.[52] Effective N_2 activation strategies increasingly focus on weakening the N≡N bond (941 kJ mol^{-1}) *via* tailored electronic structures and dual-site catalytic configurations.[51] Additionally, the lithium-mediated nitrogen reduction reaction (Li-NRR) has demonstrated comparatively higher ammonia formation rates in non-aqueous systems by forming lithium nitride intermediates that subsequently react with proton donors to release NH_3.[46] Although promising, Li-mediated systems require careful

Table 2 Annual snapshot values at decade intervals: ammonia production, annual CO_2 emissions under the BAU and Abatement Scenario (AS), percentage reduction, and technology mix. Note: values shown are annual emissions for the stated year, not decadal aggregates; true decadal aggregated totals (sum of all annual values within each decade) are reported in SI2, Table S7 S1

Year	Ammonia production (million ton)	Net CO_2 emissions in the abatement scenario (million ton)	Net CO_2 emissions in the BAU-SMR scenario (million ton)	Reduction % in the abatement scenario	Technology intervention
2010	13	89	89	0	—
2020	15	103	103	0	—
2030	21	86	145	41	10% AWE and 90% SMR with CCU
2040	29	93	201	54	20% AWE and 80% SMR with CCU
2050	40	123	280	66	35% AWE and 65% SMR with CCU
2060	56	128	389	77	40% AWE, 50% SMR with CCU, and 10% MP
2070	77	70	540	87	50% AWE, 30% SMR with CCU, and 20% MP

electrolyte management, lithium cycling stability, and strict control of parasitic reactions.

Alternative electrochemical pathways have also been explored, including reduction of nitrogen oxyanions (*e.g.*, nitrate and nitrite) to ammonia. This strategy bypasses direct N_2 activation and offers opportunities for integration with wastewater treatment and resource recovery systems, potentially improving system-level sustainability.[53,54] However, performance remains dependent on feedstock concentration, catalyst selectivity, and energy input. Non-thermal plasma activation has recently re-emerged as a complementary strategy for nitrogen fixation. Plasma-generated energetic electrons can excite N_2 into vibrationally or electronically activated states without bulk heating, partially lowering the kinetic barrier for nitrogen activation.[45,48] However, standalone plasma processes typically exhibit low energy efficiency due to radical recombination and limited product selectivity. To address these limitations, tandem plasma electrocatalysis has been proposed as a hybrid approach in which plasma first generates activated nitrogen species that are subsequently reduced at an electrochemical interface under controlled potential.[48] By decoupling activation from selective reduction, this tandem configuration aims to lower overpotentials, suppress the HER, enhance NH_3 selectivity, and enable operation under mild conditions.

However, despite advances in fundamental scientific understanding, these chemistries are at early stages of evolution. Major challenges include low ammonia production rates, poor faradaic efficiency due to competing hydrogen evolution reactions, plasma-electrode coupling efficiency, difficulty in reliable ammonia quantification, catalyst stability, and scalability limitations. An analysis of the costs of producing ammonia at large scales using an electrochemical process revealed that energy efficiency and partial current density toward ammonia are key parameters that can determine the viability of electrochemical methods.[55] An energy efficiency >30% and a partial current density of approximately 400 mA cm^{-2} are necessary for economical ammonia production. The authors concluded that substantial improvements to either the chemistries currently studied or the approach to ammonia synthesis are necessary for fully electrochemical ammonia production to be economically competitive in a large-scale centralized process.[55]

Therefore, while photocatalytic and electrocatalytic routes represent promising long-term sustainable alternatives, significant advances in fundamental science are required before they can contribute meaningfully to large-scale ammonia production. Given their current stage of development, these emerging pathways are not included in the quantitative decadal modelling framework of the present study.

3.4 Emissions under the abatement scenario

The structured technology roadmap, embodying these considerations, is presented in Table 2. Also, the identified scenarios were integrated with specific technology interventions over the decadal timescale and energy decarbonization. With the incorporation of solar energy in the grid and technology intervention consisting of 50% AWE, 30% SMR, and 20% MP, an overall reduction in CO_2 emissions as high as 87% can be achieved. Integration of 10% AWE (with a 50% share of RE flowing through the grid) and 90% SMR could lead to 41% reduction in emissions as early as 2030 (Fig. 6). The total emissions expected for the period between 2020 and 2070, along with the share of emissions abated through these technology interventions, are summarized in Table 2, demonstrating the critical role of solar energy and CCU integration and advanced production technologies such as AWE and MP in reducing emissions and driving decarbonization in the ammonia industry. Fig. 7 highlights the emission contribution in tons CO_2 eq. and per cent share from per ton production for the BAU scenario, SMR with CCU, and RE for 2070 and the abatement scenario for 2070, incorporating technologies, CCU and RE in the primary grid mix.

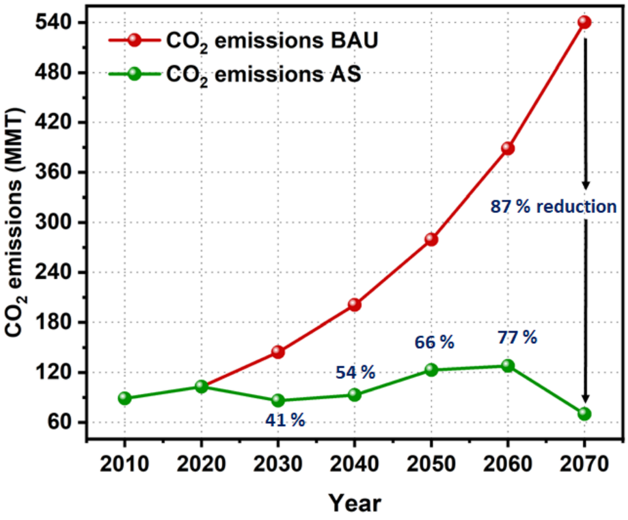

Fig. 6 Decadal reduction in total sectoral CO_2 emissions under the Abatement Scenario (AS), integrating progressive deployment of alkaline water electrolysis (AWE), methane pyrolysis (MP), carbon capture and utilization (CCU), and renewable energy (RE). The cumulative mitigation potential reaches 87% reduction by 2070 compared to BAU projections.

3.5 Environmental impacts under BAU and AS

An environmental impact analysis assessed the mid-point and end-point categories affected by ammonia production under BAU and AS. The end-point categories, representing broader classifications, include human health, ecosystem quality, climate change, and resources. In contrast, the mid-point categories provide detailed insights for determining the contributions of individual processes to various environmental impacts. Under human health, the impacts encompass carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, and respiratory organics. For ecosystem quality, the affected mid-points include aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nutrient loading, land occupation, aquatic acidification, and aquatic eutrophication. Climate change is characterized by global warming, and resources are impacted through non-renewable energy consumption and mineral extraction.

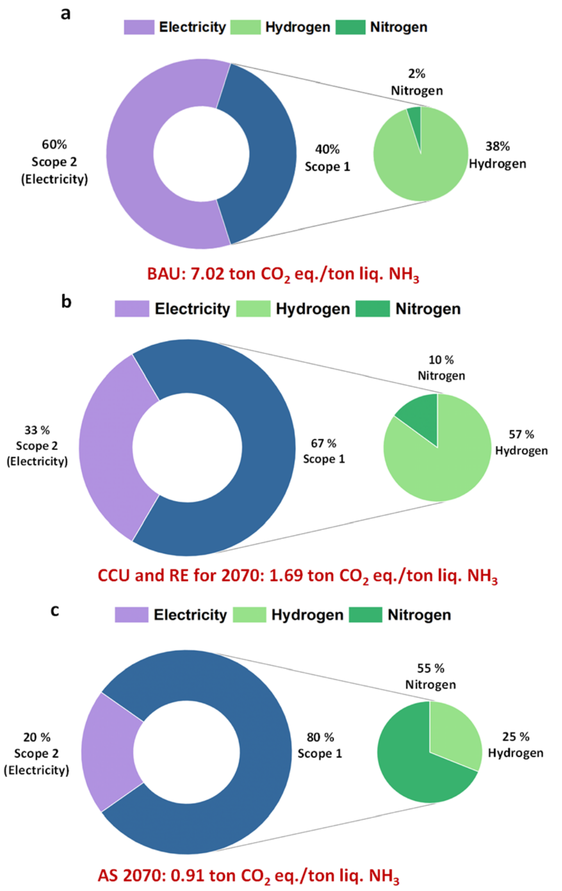

Fig. 7 Breakdown of per-ton ammonia production emissions (tons CO_2 eq. and percentage contribution) for the (a) BAU scenario (SMR-based production), (b) SMR with CCU and renewable energy integration in 2070, and (c) the integrated abatement scenario (AS) in 2070 incorporating AWE, MP, CCU, and high renewable penetration. The figure demonstrates the structural shift from fossil-derived hydrogen dominance to low-carbon hydrogen pathways.

From the analysis (Table 3), the most significant environmental impact was observed in the resources category, with non-renewable energy consumption reaching 121 127.7 MJ. Substantial impacts were also observed in the ecosystem quality category, particularly aquatic ecotoxicity (20 980.53 kg TEG water) and terrestrial ecotoxicity (13 858.02 kg TEG soil), along with climate change impacts characterized by global warming (6600.63 kg CO_2 eq). These high values highlight the substantial energy consumption and GHG emissions associated with ammonia production and its contribution to wastewater discharge into ecosystems (Fig. S28–S30 and Tables S9–S16).

However, by adopting the technologies outlined in Table 1 under the abatement scenario, the ammonia industry in India has the potential to reduce total emissions significantly, from 7.02 tons of CO_2 eq. per ton of liq. NH_3 (SMR) and 6.8 tons of CO_2 eq. per ton of liq. NH_3 (SMR + CCU) to just 0.91 tons of CO_2 eq. per ton of liq. NH_3 (AS). The transition to the AS leads to the most significant reductions in climate change, non-renewable energy consumption, terrestrial acidification/nutrient loading, respiratory inorganics, and ozone layer depletion. The sharp decline in global warming potential is primarily driven by renewable electricity integration, hydrogen pathway diversification, and CCU deployment. Similarly, the large reduction in non-renewable energy demand reflects decreasing reliance on fossil fuels as renewable energy penetration increases across future scenarios. However, several categories exhibit moderate increases, most notably mineral extraction, aquatic ecotoxicity, non-carcinogens, and ionizing radiation. The increase in mineral extraction is the most consistent trend across future scenarios and is directly associated with the material requirements of low-carbon technologies, including photovoltaic infrastructure, electrolysis systems, and CCU equipment. Aquatic ecotoxicity also increases progressively across abatement scenarios, largely driven by upstream impacts from infrastructure manufacturing, chemical use in electrolysis systems, and electricity supply chains. The rise in non-carcinogenic toxicity follows a similar trend, reflecting expanded material supply chains rather than direct process emissions. Ionizing radiation exhibits moderate increases due to upstream electricity production processes, even under renewable-dominated grids,

Table 3 Environmental impact categories and respective impacts under BAU and AS

Midpoint category	Endpoint category	Unit	Environmental impact scenario (SMR)	Environmental abatement scenario (2070)
Carcinogens	Human health	kg C_2H_3Cl eq.	12.93	10.58
Non-carcinogens		kg C_2H_3Cl eq.	26.93	50.66
Respiratory inorganics		kg PM2.5 eq.	2.15	0.612
Ionizing radiation		Bq C-14 eq.	2503.31	1499.92
Ozone layer depletion		kg CFC-11 eq.	0.000222	0.00004
Respiratory organics		kg C_2H_4 eq.	5.14	0.34
Aquatic ecotoxicity	Ecosystem quality	kg TEG water	20 980.53	23 332.03
Terrestrial ecotoxicity		kg TEG soil	13 858.02	13 311.41
Terrestrial acidification/nutrients		kg SO_2 eq.	44.73	10.16
Land occupation		m^2org.arable	13.51	8.98
Aquatic acidification		kg SO_2 eq.	8.62	2.81
Aquatic eutrophication		kg PO_4 P-lim	0.142	0.113
Global warming	Climate change	kg CO_2 eq.	6600.63	741.72
Non-renewable energy	Resources	MJ primary	121 127.7	6919.78
Mineral extraction		MJ surplus	43.96158	115.596

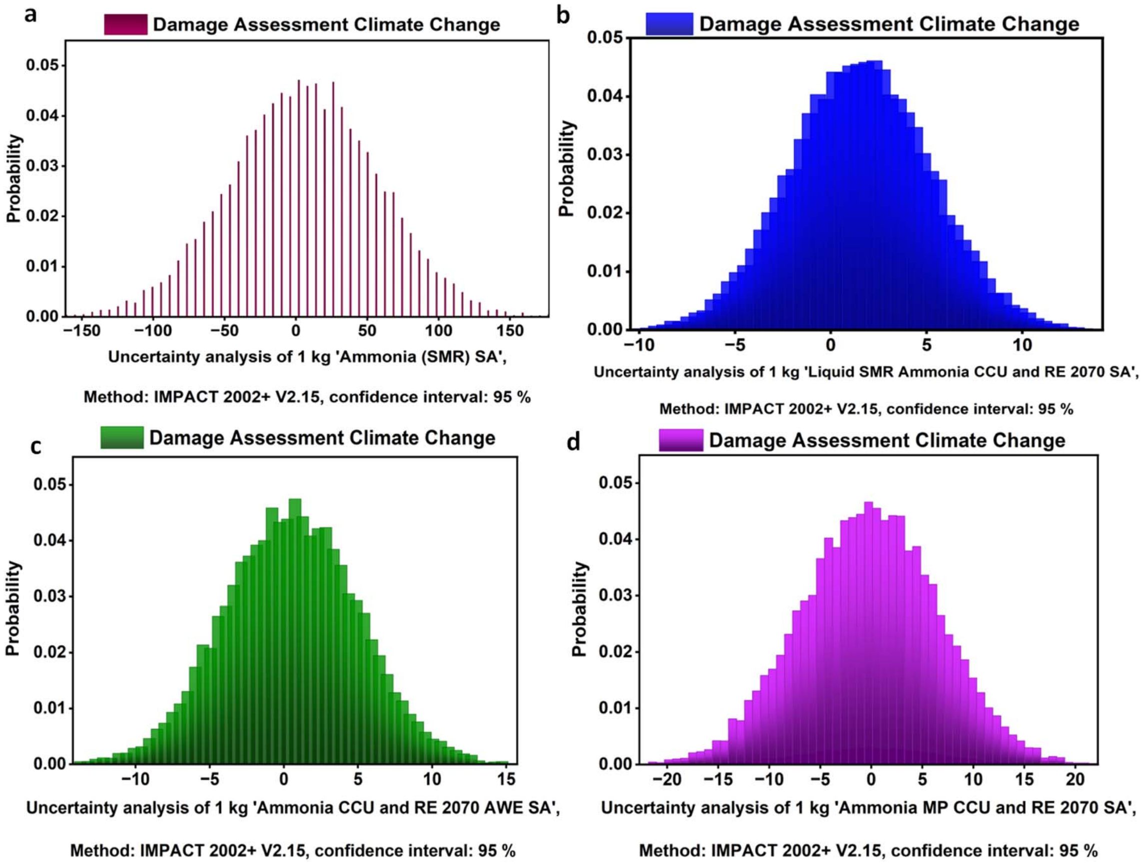

Fig. 8 Monte Carlo uncertainty distributions (95% confidence interval) for the climate change damage indicator associated with ammonia production across different pathways: (a) conventional SMR (baseline), (b) SMR with CCU and renewable electricity (2070), (c) alkaline water electrolysis (AWE) with CCU and renewable electricity (2070), and (d) methane pyrolysis (MP) with CCU and renewable electricity (2070). The probability distributions illustrate the variability of life cycle climate impacts arising from parameter uncertainty in energy inputs, technology performance, and background datasets, highlighting the robustness of emission reduction trends across future low-carbon ammonia scenarios.

highlighting the influence of background datasets in energy system modelling. In contrast, land occupation shows only modest variation, indicating that infrastructure expansion contributes but does not dominate the overall environmental profile.

Overall, integrating advanced technologies, renewable energy sources, and CCU into ammonia production can substantially mitigate environmental, social, and economic impacts. These interventions could transform ammonia production into a more sustainable process, aligning it with global sustainability goals.

3.6 Uncertainty analysis

A sensitivity/uncertainty analysis was performed to evaluate the influence of key assumptions, including grid decarbonization and technology performance, on projected emission trajectories. The uncertainty analysis (Monte Carlo simulation, 95% confidence interval) of the climate change damage indicator reveals clear differences in both impact magnitude and robustness across ammonia production pathways. Conventional SMR exhibits the highest mean impact and the widest distribution, indicating greater sensitivity to input variability and higher overall uncertainty. Integration of CCU and renewable energy shifts the distribution toward lower impact values and reduces variability, demonstrating improved environmental performance and modelling stability (Fig. 8 and S31). Renewable ammonia production (AWE with CCU and RE) shows consistently lower impacts with comparatively narrower distributions, suggesting more robust decarbonization potential. MP scenarios also indicate reduced climate impacts relative to SMR but display a broader spread, reflecting higher uncertainty associated with emerging technology assumptions and co-product handling. The results highlight that decarbonization pathways not only lower average climate impacts but also enhance the robustness of environmental performance outcomes.

4 Conclusion

This study systematically evaluates the Indian ammonia industry's carbon emissions and decarbonization potential under various scenarios. The findings reveal that under the BAU scenario, the Indian ammonia production industry could result in nearly doubling of annual CO_2 emissions from approximately 145 MMT CO_2 in 2030 to 280 MMT CO_2 by 2050 and 540 MMT CO_2 by 2070, driven by rising ammonia demand projected to reach 77 MMT. We suggest a few essential technology interventions that the Indian ammonia industry should consider adopting between now and 2070. These suggestions are based on the current and anticipated TRLs of specific technologies between now and 2070 and the industry's readiness to adopt them at scale. Subject to their implementation, we project that the peak emissions will occur around 2060, followed by reductions thereafter. The LCA results indicate that transitioning to renewable-energy-based ammonia production could reduce the carbon footprint by over 87%, reducing emissions to 0.91 CO_2 eq. tons per ton of liq. NH_3 annually by 2070 under the abatement scenario (AS). Hydrogen production through AWE powered by solar or wind energy has the maximum potential to reduce emissions, contributing up to 50% of the total abatement. Methane pyrolysis could reduce emissions by 15–20%, while CCU technologies could address 10–15% of residual emissions. However, RE and CCU face significant challenges because of intermittent supply and the urgent need for large-scale energy storage. India's transmission and distribution infrastructure will need substantial capacity enhancement to accommodate the increased flow of RE into the grid. Further impact assessments highlight other environmental concerns, such as high terrestrial and aquatic ecotoxicity under BAU and AS scenarios, necessitating additional interventions. Furthermore, ancillary emissions from ammonia's end use, particularly as a fertilizer, remain a significant challenge. To achieve comprehensive emission reductions, equal emphasis must be placed on developing low-emission fertilizers alongside decarbonizing ammonia production.

The results of this study also highlight that deep decarbonisation of India's ammonia sector will require coordinated policy support across the energy and climate sectors as well as the industry. Since deploying renewable electricity and low-carbon hydrogen contribute to the largest share of emission reduction (up to 87% by 2070), accelerated expansion of renewable energy capacity as well as preferential access for industrial users are essential. Deployment of energy storage technologies, long-term renewable power purchase agreements and grid modernization will be critical to reduce scope 2 emissions. In the near term, carbon capture retrofits in existing SMR-based plants can deliver measurable emission reductions. However, large-scale deployment will require supportive carbon pricing mechanisms, fiscal incentives, and development of CO_2 transport and storage infrastructure, particularly in industrial clusters. To enable structural transition, targeted incentives under India's National Green Hydrogen Mission, such as capital subsidies for electrolyzers and green hydrogen procurement mandates for fertilizer producers, can accelerate adoption of alkaline water electrolysis. A phased carbon market or emission trading mechanism would further improve the economic viability of low-carbon ammonia pathways. By addressing these challenges through coordinated efforts, the Indian ammonia industry can achieve near-zero emissions by 2070, which aligns well with India's stated net-zero goals and fosters a balanced approach to economic growth and environmental stewardship.

Author contributions

TM, HS, PK, and YJ: methodology, data collection & analysis, writing of the draft manuscript and visualization. RK: data collection. S. Venkata Mohan: resources, data curation, review & editing, supervision. Swaminathan Sivaram: defining the problem statement, conceptualization, resources, data validation, review & editing, supervision, and funding.

Conflicts of interest

There is no conflict of interest to declare.

Abbreviations

AWE	Alkaline water electrolysis
MP	Methane pyrolysis
AS	Abatement scenario
BAU	Business as usual
CO_2	Carbon dioxide
H_2	Hydrogen
NH_3	Ammonia
N_2	Nitrogen
MMT	Million tons
CCU	Carbon capture and utilization
IFA	International Fertilizer Association
FAI	Fertiliser Association of India
AEA	Ammonia Energy Association
IMF	International Monetary Fund
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MJ	Megajoule
GJ	Gigajoule
GT	Giga tons
OECD	Organisation for Economic Co-operation and Development
PFC	Perfluorocarbon
PM2.5	Particulate matter (2.5 microns or smaller)
RE	Renewable energy
NRR	Nitrogen reduction reaction
HER	Hydrogen evolution reaction
SF6	Sulfur hexafluoride
TEG	Toluene equivalent global
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
IEA	International Energy Agency
WBCSD	World Business Council for Sustainable Development
WRI	World Resources Institute

Data availability

The data supporting the findings of this study are available within the article and its supplementary information (SI).

Supplementary information: life cycle inventory (LCI) data, process descriptions, system boundary definitions, Sankey diagrams, correlation analyses, and midpoint life cycle impact assessment results for all ammonia production pathways investigated. See DOI: https://doi.org/10.1039/d5su00936g.

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References

1 M. R. Moghadam, A. Bazmandegan-Shamili and H. Bagheri, in *Progresses in Ammonia: Science, Technology and Membranes*, Elsevier, 2024, pp. 1–32.

2 Kleinman Centre of Energy Policy, Ammonia's Role in a Net-Zero Hydrogen Economy, 2023, https://kleinmanenergy.upenn.edu/research/publications/ammonias-role-in-a-net-zero-hydrogen-economy/, Accessed on 5th January, 2025.

3 The Ammonia Energy Association, Annual Report, 2023, https://ammoniaenergy.org/wp-content/uploads/2024/05/AEA-2023-Annual-Report-0524_final.pdf, Accessed on 5th January, 2025.

4 International Energy Agency (IEA), Ammonia Technology Roadmap, 2021, https://www.iea.org/reports/ammonia-technology-roadmap, Accessed on 5th January, 2025.

5 The Royal Society, Ammonia: zero-carbon fertilizer, fuel and energy store, 2020, https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf, Accessed on 5th January, 2025.

6 IRENA and AEA, Innovation Outlook: Renewable Ammonia, International Renewable Energy Agency, Abu Dhabi, Ammonia Energy Association, Brooklyn, 2022, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf, Accesed on 5th January, 2025.

7 Council of Energy, Environment and Water (CEEW), Economic Feasibility of Green Ammonia Use in India's Fertiliser Sector, 2024, https://www.ceew.in/sites/default/files/ceew-giz-economic-feasibility-of-green-ammonia-use-in-indias-fertiliser-sector.pdf, Accessed on 5th January, 2025.

8 N. Ayog, Harnessing Green Hydrogen Opportunities for Deep Decarbonisation In India, 2022, https://www.niti.gov.in/sites/default/files/2022-06/Harnessing_Green_Hydrogen_V21_DIGITAL_29062022.pdf, Accessed on 5th January, 2025.

9 Indian Agricultural Research Institute (IARI), Vision 2050, https://www.iari.res.in/files/vision/vision-2050.pdf.

10 World Economic Forum, Ammonia industry net-zero tracker, 2023, Accessed on 5th January, 2025 https://www3.weforum.org/docs/WEF_Net_Zero_Tracker_2023_AMMONIA.pdf.

11 R. Gupta, D. Malik, S. Sankhe and N. Unni, *McKinsey Sustainability, Decarbonising India: Charting a Pathway for Sustainability*, 2022, https://www.mckinsey.com/capabilities/sustainability/our-insights/decarbonising-india-charting-a-pathway-for-sustainable-growth, Accessed on 5th Jan 2024.

12 S. C. D'Angelo, S. Cobo, V. Tulus, A. Nabera, A. J. Martin, J. Pérez-Ramírez and G. Guillen-Gosalbez, *ACS Sustain. Chem. Eng.*, 2021, **9**(29), 9740–9749.

13 Y. Bicer, I. Dincer, G. Vezina and F. Raso, *Environ. Manag.*, 2017, **59**, 842–855.

14 Y. Bicer and I. Dincer, *Int. J. Hydrogen Energy*, 2017, **42**(33), 21559–21570.

15 Y. Bicer, I. Dincer, C. Zamfirescu, G. Vezina and F. Raso, *J. Clean. Prod.*, 2016, **135**, 1379–1395.

16 S. Vinardell, P. Nicolas, A. M. Sastre, J. L. Cortina and C. Valderrama, *ACS Sustain. Chem. Eng.*, 2023, **11**(44), 15975–15983, https://pubs.acs.org/doi/pdf/10.1021/acssuschemeng.3c04694.

17 A. Makhlouf, T. Serradj and H. Cheniti, *Environ. Impact Assess. Rev.*, 2015, **50**, 35–41.

18 Y. Li, Z. Zhang, Q. Wang, X. Long, Y. Cao, H. Yang and Q. Yang, *J. Environ. Manag.*, 2023, **345**, 118848.

19 S. Ghavam, M. Vahdati, I. G. Wilson and P. Styring, *Front. Energy Res.*, 2021, **9**, 580808, https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2021.580808/full.

20 B. Jabarivelisdeh, E. Jin, P. Christopher and E. Masanet, *Technical Report*, 2022, https://www.c-thru.org/wp-content/uploads/2022/12/Ammonia-Technical-Brief-June2022.pdf, Accessed on 5th May, 2025.

21 F. Čejka, *Bryan Research & Engineering*, LLC, 2022, https://www.bre.com/PDF/Comparison-of-Process-Options-for-Sustainable-Ammonia-Production.pdf, Accessed on 5th May, 2025.

22 V. M. Zade, P. R. Athawale, H. Kopperi, S. V. Mohan and D. S. Reddy, *ACS Sustain. Chem. Eng.*, 2024, **12**(42), 15671–15681, https://pubs.acs.org/doi/abs/10.1021/acssuschemeng.4c06361.

23 S. Dahiya, R. Katakojwala, S. Ramakrishna and S. V. Mohan, *Mater. Circ. Econ.*, 2020, **2**, 1–28.

24 International Monetary Fund (IMF), India Report, 2023, https://www.imf.org/en/Countries/IND, Accessed on 5th Jan 2025.

25 Projects & Development India Limited, 2024, https://www.pdilin.com/fertilisers.php.
26 MNRE, *Project-National Green Hydrogen Mission of India*, 2024, https://nghm.mnre.gov.in/project?cat=16&language=en, Accesed on 5th January, 2025.
27 S. Chopra, *Indian J. Econ. Dev.*, 2018, **14**(3), 410–419.
28 IEEFA, India's Renewable Energy Journey: Short-Term Hiccups but Long-Term Trajectory Intact, https://ieefa.org/sites/default/files/2022-10/IndiaREJourney_Oct2022.pdf, Accessed on 5th January, 2025.
29 H. Tüysüz, *Acc. Chem. Res.*, 2024, **57**(4), 558–567, DOI: 10.1021/acs.accounts.3c00709.
30 U. Bossel and B. Eliasson, *Energy and the Hydrogen Economy*, Methanol Institute, Arlington, VA, 2003, https://afdc.energy.gov/files/pdfs/hyd_economy_bossel_eliasson.pdf.
31 AEA, Technology status: ammonia production from electrolysis-based hydrogen, 2023, https://ammoniaenergy.org/articles/technology-status-ammonia-production-from-electrolysis-based-hydrogen/, Accessed on 5th January, 2025.
32 U. Gupta, *Acme to Build 1.5 GW Green Hydrogen Project in Tamil Nadu*, 2022, https://www.pv-magazine-india.com/2022/07/05/acme-announces-1-5-gw-green-hydrogen-project-in-tamil-nadu/, Accessed on 5th January, 2025.
33 AM Green Website, 2024, https://www.amgreen.com/, Accessed on 5th January, 2025.
34 N. Sánchez-Bastardo, R. Schlögl and H. Ruland, *Ind. Eng. Chem. Res.*, 2021, **60**(32), 11855–11881, DOI: 10.1021/acs.iecr.1c01679.
35 M. R. G. Pangestu, Z. Malaibari, A. Muhammad, F. N. Al-Rowaili and U. Zahid, *Energy Fuels*, 2024, **38**(15), 13514–13538, DOI: 10.1021/acs.energyfuels.4c01551.
36 Ammonia Energy Association (AEA), India: a future ammonia energy giant, 2023, https://ammoniaenergy.org/articles/india-a-future-ammonia-energy-giant/, Accessed on 5th January, 2025.
37 Prime Minister of India, National Statement at COP26 Summit, Glasgow (01 Nov 2021), https://www.pmindia.gov.in/en/news_updates/national-statement-by-pm-at-cop26-summit-in-glasgow/, Accessed on 5th Jan 2025.
38 NITI Aayog, Carbon Capture, Utilisation and Storage (CCUS): Policy Framework and Its Deployment Mechanism in India, 2022, Accessed on 5th January 2025.
39 NITI Ayog, *Harnessing Opportunities for Deep Decarbonization in India: New Report*, 2023, Accessed on 5th January 2025.
40 G. Qing, R. Ghazfar, S. T. Jackowski, F. Habibzadeh, M. M. Ashtiani, C. P. Chen, M. R. Smith III and T. W. Hamann, *Chem. Rev.*, 2020, **120**(12), 5437–5516.https://pubs.acs.org/doi/10.1021/acs.chemrev.9b00659.
41 X. Yang, S. Mukherjee, T. O'Carroll, Y. Hou, M. R. Singh, J. A. Gauthier and G. Wu, *Angew. Chem., Int. Ed.*, 2023, **62**(10), e202215938. https://onlinelibrary.wiley.com/doi/full/10.1002/anie.202215938.
42 D. Ye and S. C. E. Tsang, *Nat. Synth.*, 2023, **2**(7), 612–623. https://www.chem.ox.ac.uk/publication/1533651/scopus.
43 A. J. Martín, T. Shinagawa and J. Pérez-Ramírez, *Chem*, 2019, **5**(2), 263–283. https://www.sciencedirect.com/science/article/pii/S245192941830490X.
44 C. Li, T. Wang and J. Gong, *Trans. Tianjin Univ.*, 2020, **26**(2), 67–91. https://link.springer.com/article/10.1007/s12209-020-00243-x.
45 M. A. Yusov and K. Manthiram, *Nat. Mater.*, 2024, **23**(1), 31–32. https://www.nature.com/articles/s41563-023-01747-2.
46 W. Chang, A. Jain, F. Rezaie and K. Manthiram, *Nat. Catal.*, 2024, **7**(3), 231–241. https://www.nature.com/articles/s41929-024-01115-6.
47 N. Lazouski, K. J. Steinberg, M. L. Gala, D. Krishnamurthy, V. Viswanathan and K. Manthiram, *ACS Catal.*, 2022, **12**(9), 5197–5208. https://pubs.acs.org/doi/10.1021/acscatal.2c00389.
48 W. Wang, Y. Wang and X. Tu, *Curr. Opin. Green Sustainable Chem.*, 2025, **51**, 100986. https://www.sciencedirect.com/science/article/pii/S245222362400107X.
49 M. Wang, M. A. Khan, I. Mohsin, J. Wicks, A. H. Ip, K. Z. Sumon, C. T. Dinh, E. H. Sargent, I. D. Gates and M. G. Kibria, *Energy Environ. Sci.*, 2021, **14**(5), 2535–2548. https://pubs.rsc.org/en/content/articlelanding/2021/ee/d0ee03808c.
50 X. Xue, R. Chen, C. Yan, P. Zhao, Y. Hu, W. Zhang, S. Yang and Z. Jin, *Nano Res.*, 2019, **12**(6), 1229–1249. https://link.springer.com/article/10.1007/s12274-018-2268-5.
51 Y. Xiong, B. Li, Y. Gu, T. Yan, Z. Ni, S. Li, J. L. Zuo, J. Ma and Z. Jin, *Nat. Chem.*, 2023, **15**(2), 286–293, https://www.nature.com/articles/s41557-022-01088-8.
52 A. Anwar, S. Y. T. Al Khalil, M. Alherbawi and Y. Bicer, *RSC Sustainability*, 2025, **3**(6), 2644–2658. https://pubs.rsc.org/en/content/articlelanding/2025/su/d5su00019j.
53 M. Jiang, X. Huang, D. Luo, C. Tian and Z. Jin, *Nano Energy*, 2025, 110683. https://www.sciencedirect.com/science/article/pii/S2211285525000424.
54 M. Jiang, X. Chen, F. Chen, M. Wang, X. Luo, Y. He, C. Wu, L. Zhang, X. Li, X. Liao and Z. Jiang, Effective N2 activation strategies for electrochemical ammonia synthesis, *Chem*, 2025, **11**(4), 102441 https://www.sciencedirect.com/science/article/pii/S2451929425000312?via%3Dihub.
55 N. Lazouski, A. Limaye, A. Bose, M. L. Gala, K. Manthiram and D. S. Mallapragada, *ACS Energy Lett.*, 2022, **7**(8), 2627–2633. https://pubs.acs.org/doi/10.1021/acsenergylett.2c01197.