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GREEN UREA

Economic and Environmental Benefits of a Low-Carbon Future

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List of Abbreviations

BAT	Best Available Technology
CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
CO_2e	Carbon dioxide-equivalent
DAP	Diammonium phosphate
GHG	Greenhouse gas
HYV	High Yielding Variety
H_2	Hydrogen
LCOU	Levelised Cost of Urea
LCP	Low Carbon Pathway
MT	Metric Tonne
NGHM	National Green Hydrogen Mission
NG	Natural Gas
N_2	Nitrogen
NUE	Nitrogen Use Efficiency
NPK	Nitrogen, Phosphorous and Potassium
O_2	Oxygen
ODS	Ozone-Depleting Substance
PAT	Perform, Achieve and Trade
SMR	Steam Methane Reforming
UAP	Urea-Ammonium Phosphates

Summary for Stakeholders

1. Context

Since the Green Revolution, which kicked off in the 1960s as a response to India's low agricultural productivity and need to import food, the nation has relied on Urea to provide the nitrogen necessary for higher crop yields and food security. But this reliance has come at a cost to the economy and the environment.

Urea use has a significant role in three major environmental challenges: nitrogen pollution, ozone layer depletion and climate change. As Urea production depends entirely on fossil fuels, it contributes to greenhouse gas (GHG) emissions during production. Nitrous oxide (N_2O) emitted from agricultural fields due to the use of Urea is also a potent GHG and an ozone-depleting substance (ODS). Its GHG potential is 300 times that of CO_2, and its ozone-depleting potential is similar to that of many hydrochlorofluorocarbon refrigerants. N_2O is now the largest ODS emitted through human activities.

In addition, nitrogen pollution of surface water and groundwater has reached alarming levels in many states of India. It is estimated that the cost of water pollution due to nitrogen is about $30 billion yearly, about the same as the turnover of the Urea industry. There is also widespread soil sickness due to imbalanced application of Urea.

Presently, about 4.3% of India's GHG emissions are due to Urea production and use in agriculture. As India aims for a net-zero economy, it is crucial to explore pathways to reduce carbon emissions in Urea manufacturing and usage and support a green transition.

This study approaches the solutions to the challenges mentioned above from Demand-side and Supply-side interventions. On the demand side, the study models Urea consumption up to 2050 by analysing six scenarios. Each of these considers different business interventions, policy mandates, and environmental conditions that could influence future demand. Effectively, each scenario represents different levels of concern towards optimising India’s demand for Urea.

The supply-side approach considers how India's domestic Urea manufacturing industry can be decarbonised while still meeting national requirements in the most cost-effective manner. This supply-side modelling is undergirded by a detailed analysis of each of the currently operating Urea manufacturing plants. Different production pathways – that produce Gray, Blue and Green Urea, respectively - are considered for each plant to project the Levelised Cost of Urea (LCOU) production up to 2050. Thus, the supply-side modelling helps identify optimal pathways to producing Urea cost-effectively while eliminating the associated GHG emissions from production.

Finally, the demand-side and supply-side modelling results are combined to develop a Low-Carbon Pathway for decarbonising the production and consumption of Urea in India.

The Low Carbon Pathway presents an economically viable and environmentally sound strategy for the manufacture and consumption of Urea with minimal GHG emissions and other related environmental pollution. Considering the growing demand for food production in India as its population continues to grow in terms of size and affluence, this strategy is crucial to India's food security and agricultural economy.

2. State of Urea Consumption

- Urea is the most extensively and widely used fertiliser in the country. During 2022-23, Urea accounted for 56% of all fertilisers and nearly 80% of all the nitrogenous fertilisers used.
- The consumption of Urea has grown from 6.2 million metric tonnes (MMT) in 1980-81 to 35.7 MMT in 2022-23.
- India has the highest dependence on Urea. In most big agricultural economies, Urea only provides between 24% to 57% of total nitrogenous fertiliser; in India, it is close to 80%.
- In the 1970s, the Urea subsidy accounted for 10–20% of the production cost; now, it stands at 85-90%. This widening gap between production costs and retail prices, coupled with a significant increase in consumption, has caused the overall Urea subsidy to rise exponentially. Since the 1980s, the Urea subsidy has increased nearly 340 times at current prices (from less than ₹500 crore in 1980–81 to ₹168,692 crore in 2022–23).
- The overuse of Urea has reached unsustainable proportions. While the recommended average ratio of NPK application on Indian agricultural lands is 4:2:1, in 2022-23, the ratio of actual applications was 11.8:4.6:1.
- The average efficiency of nitrogenous fertilisers in India in terms of actual uptake by the target crops is estimated to be low compared to other countries. Nitrogen use efficiency is 35% in India, compared to a North American average of 53%. Certain European countries report values closer to 80%. Thus, more than 60% of nitrogenous fertilisers are lost to the environment, leading to water and air pollution and soil degradation.
- The use of nitrogenous fertiliser in India has reached a point of diminishing returns. For instance, the total foodgrain production per unit nitrogenous fertiliser consumption (as N) has more than halved in the last 40 years—from 35.2 MT/MT in 1980-81 to 16.3 MT/MT in 2022-23.

3. State of Urea Production

- Urea production has increased from 3.4 MMT to 28.5 MMT in 2022-23. India is now the world's second-largest producer of Urea, behind China.
- The Urea industry in India comprises 36 plants of varied sizes spread throughout the country. A significant number are concentrated in Uttar Pradesh, Gujarat, and Rajasthan. The country's total Urea manufacturing capacity currently stands at 31.3 MMT.
- Urea plants in India are relatively old– most existing manufacturing facilities were established between 1970 and 2000. Approximately 45% of these units are over 40 years old. The average capacity-weighted age of all the plants is 29 years.

- Urea manufacturing in India heavily relies on imported Natural Gas (NG). In 2022-23, 84% of Urea was produced from imported NG, and about 21% of total consumption was imported Urea. Effectively, 87.5% of Urea consumed in the country was either based on imported NG or imported Urea.

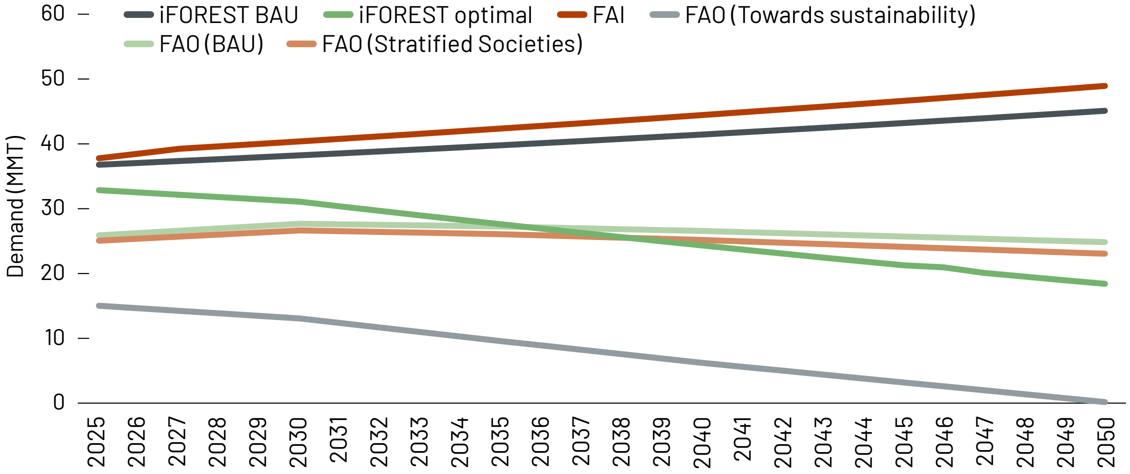
4. GHG Emissions

- In India, an average of 0.7 MT CO_2e is emitted for each MT of Urea during production. However, production emissions are only a small part of Urea's lifecycle GHG emissions. The majority of emissions - about 85% — come from its use in agriculture.
- The total GHG emissions from Urea production and use in India in 2022-23 were 171 MMT CO_2e. This amounts to 4.3% of national GHG emissions and 21.7% of agricultural GHG emissions.

5. Demand-Side Optimisation

- The study evaluated Urea demand projections from multiple sources, including the Fertiliser Association of India (FAI), the Food and Agriculture Organisation (FAO), and the scenarios developed by iFOREST. These projections offer a comprehensive outlook on the future of Urea consumption in India, considering different scenarios and policy interventions.
- Six scenarios were analysed in total—one from FAI, three from FAO, and two from iFOREST. These Scenarios show that Urea demand in 2050 can vary between zero in FAO's Towards Sustainability Scenario and 49.1 MMT in FAI's scenario.
- In iFOREST's Business-As-Usual Scenario, Urea demand in 2050 can reach about 45 MMT, while in iFOREST's Optimal Pathway, it can be reduced to 18.2 MMT.

Graph 1: Urea demand projection in different scenarios



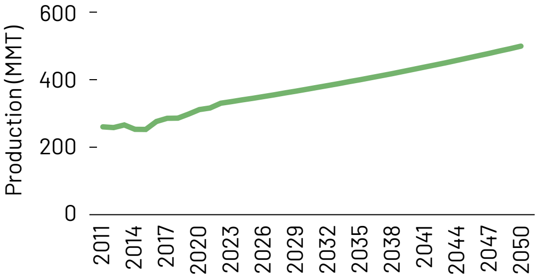
Source: FAI, FAO, iFOREST

- The iFOREST's Optimal Pathway seems most appropriate considering the government's policy thrust and the intended outcomes. This scenario will require policies to promote 30:30:30. That is, by 2050, India should target to:
  i. Increase the area under non-chemical farming to 30%;
  ii. Improve nitrogen use efficiency by 30%; and,

iii. Reduce the proportion of Urea in nitrogenous fertilisers by 30%.

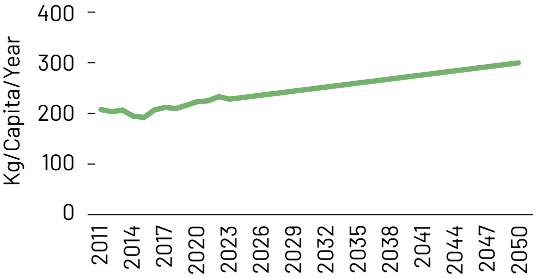
- Under the Optimal Pathway:
  i. Foodgrain production in India is projected to increase from 330 MMT in 2022-23 to 500 MMT in 2050-51.
  ii. Per capita food availability is expected to rise from 230 kg per year in 2022-23 to 300 kg per year by 2050-51.
  iii. Nitrogen demand is anticipated to decrease from 20.2 MMT in 2022-23 to 14.1 MMT in 2050. Correspondingly, Urea demand will decline from 35.7 MMT in 2022-23 to 18.2 MMT by 2050.
  iv. Greenhouse gas emissions from Urea use are expected to drop from 150 MMT CO_2e currently to 77 MMT CO_2e by 2050. This amounts to a per capita emission of 0.05 MT (46 Kg) of CO_2e per year. This relatively small amount of emission can be easily sequestered through alternative means, including in India's forests.

Graph 2: Food Grain Production



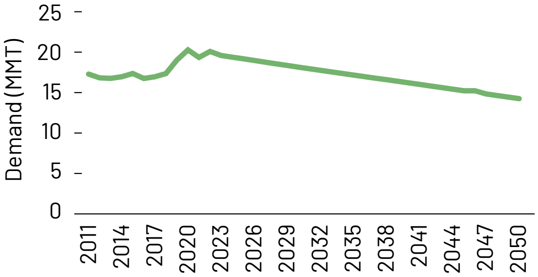
Source: iFOREST analysis

Graph 3: Per Capita Food Grain Availability



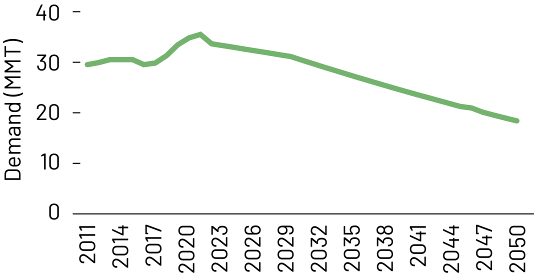
Source: iFOREST analysis

Graph 4: Nitrogen Demand Projection



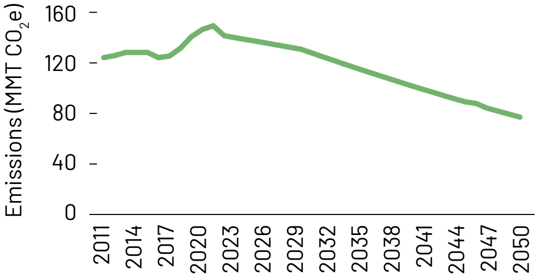
Source: iFOREST analysis

Graph 5: Urea Demand Projection



Source: iFOREST analysis

Graph 6: GHG Emissions from Urea Use



Source: iFOREST analysis

6. Supply-Side Decarbonisation

The process of making Urea (NH_2CONH_2) starts with producing Ammonia (NH_3), then reacting NH_3 with Carbon dioxide (CO_2). Producing Ammonia requires pure Hydrogen (H_2) and Nitrogen (N_2). The challenging part is producing H_2, usually obtained through Steam Methane Reformation (SMR) of Natural Gas (CH_4) or via electrolysis to produce Green H_2. CO_2 is generated during SMR or sourced from fossil fuel plants using carbon capture and storage (CCS) technology. N_2 is obtained through air separation technology.

The supply-side modelling explores different Urea production routes—Grey, Blue, and Green Urea—to achieve cost-effective decarbonisation. It also explores whether the plants should be modified/upgraded (Brownfield) or a completely new plant should be set up at the site of the existing plant (Greenfield). Each route represents a different level of technological advancement, economic costs and environmental impact:

a) **Grey Urea:** The traditional method of Urea production, which is reliant on NG, results in high GHG emissions. This pathway represents the current state of Urea production in India.

b) **Blue Urea:** Incorporates CCS technologies to reduce emissions associated with Urea production. This pathway offers a transitional solution that leverages existing infrastructure while reducing environmental impact.

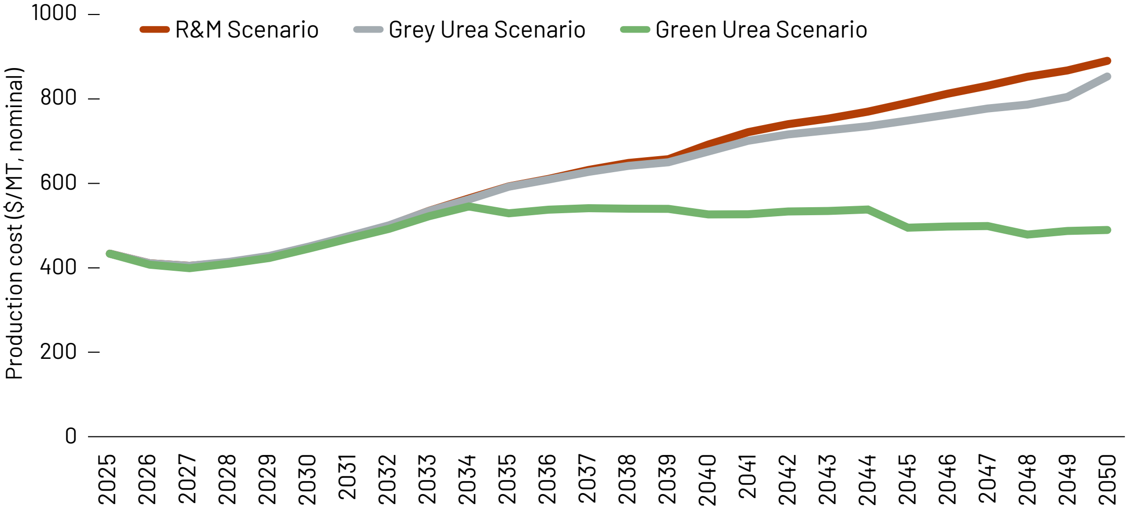
c) **Green Urea:** Utilises renewable energy sources, such as solar and wind, to produce Urea, resulting in minimal GHG emissions. This pathway represents the ultimate goal for a sustainable and environmentally friendly Urea production process.

- **Modelling Methodology:** Economic modelling using various scenarios was undertaken to assess decarbonisation pathways for the industry in India. The study evaluates the LCOU for each pathway, considering factors such as capital investment, operational costs, and technical and financial parameters.

  The modelling was done in two phases. In Phase 1, sectoral modelling was done to assess the economic feasibility of decarbonising the Urea industry in India from a central planner's perspective. In Phase 2, plant-level modelling was done for all 36 existing plants to assess the economic feasibility of decarbonisation strategies tailored for each plant.

- The sectoral and plant-level modelling results show that it is economically prudent to move the entire fleet of Urea manufacturing plants to Green Urea by 2050. The LCOU for the Green Urea Scenario is \$475/MT, compared to \$550/MT in the Renovation and Modernisation (R&M) Scenario and \$540/MT in the Grey Urea Scenario. This shows that continuing the practice of R&M to extend the life of existing Urea plants is the most expensive way to produce Urea in India. On the other hand, the cheapest Urea can be produced through the Green Urea route.

Graph 7: Nominal cost of production of Urea: 2025-2050



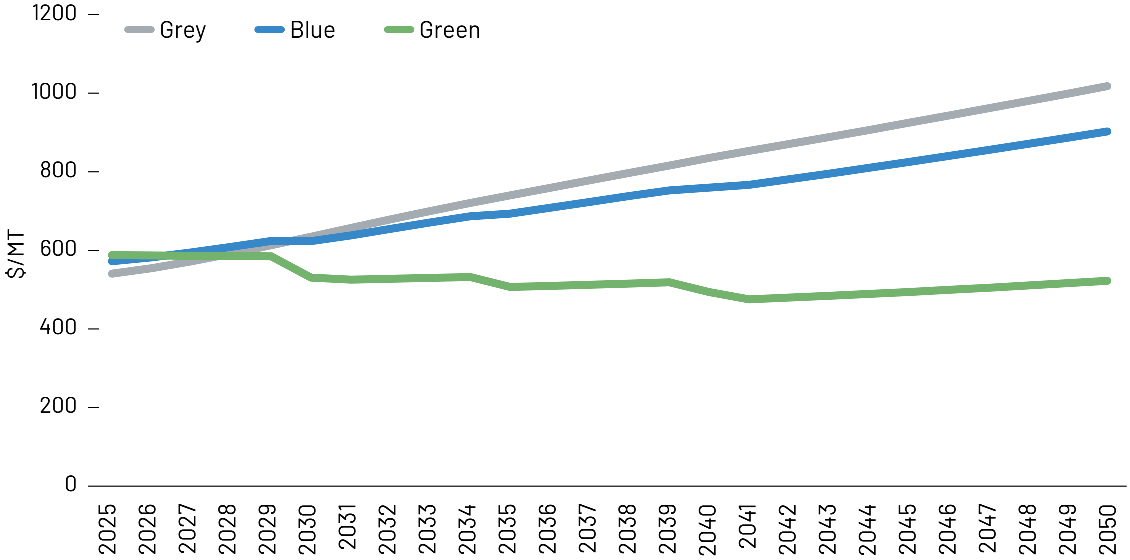
Source: iFOREST analysis

Notes:

- R&M Scenario: This scenario assumes that the existing plants will continue as Grey Urea plants through regular renovation and modernisation.
- Grey Urea Scenario: This scenario assumes that the existing plants will be scrapped and converted into Greenfield Green Urea plants after completing 60 years of life.
- Green Urea Scenario: Under this, plants are transitioned to Brownfield/Greenfield Urea based on cost effectiveness.

- The result also shows that installing Greenfield Gray or Blue Urea plants in India after 2028 lacks economic rationale, as the lowest LCOU post-2028 is for the Green Ureal plant.

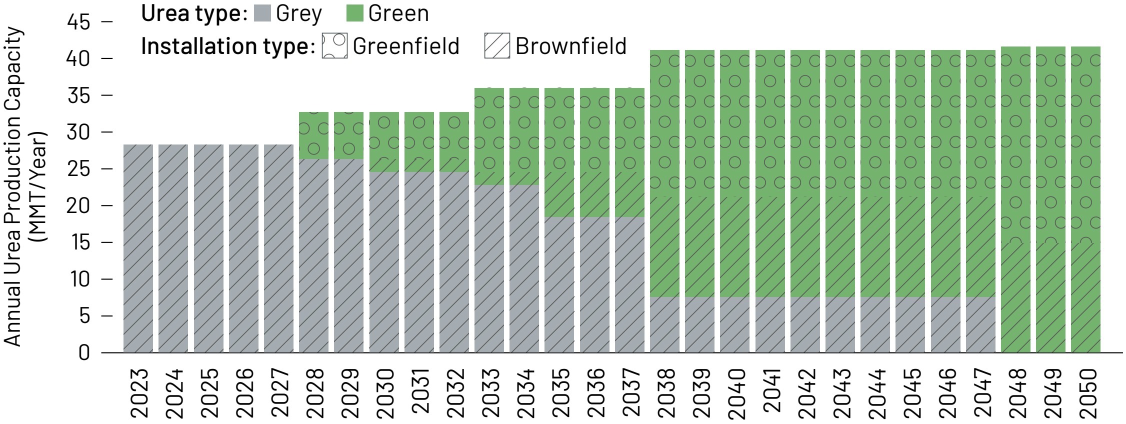
Graph 8: LCOU of a Model Greenfield Gray, Blue and Green Urea Plant Installed between 2025-2050



Source: iFOREST analysis

- Thus, Green Urea is the most economically viable option for the Indian Urea sector. If adopted as a policy, all existing Urea plants can be transitioned to Brownfield/Greenfield Green Urea by 2050. Additionally, production capacity will be enhanced as older, smaller plants are replaced with larger Green Urea plants.

Graph 9: Green Urea Scenario



Source: iFOREST analysis

7. Low Carbon Pathways

The Low Carbon Pathway (LCP) for the Urea sector in India comprises the iFOREST Optimal Pathway on the demand side and the Green Urea Scenario on the supply side.

- Under the LCP, Urea production increases, consumption decreases, imports are eliminated, exports rise, subsidies are reduced, GHG emissions decline, and water and air pollution are mitigated. Additionally, both energy and food security are enhanced.
- The main economic advantages of the LCP over the Business-As-Usual (BAU) are:
  i. The total Urea demand from 2025 to 2050 in the LCP is 675 MMT compared to 1058 MMT in the BAU. This 36% reduction in Urea demand translates into a saving of $250 billion.
  ii. In BAU, India will have to import about 93 MMT of Urea during 2025-50, at a cost of $42 billion. In contrast, in the LCP, it can potentially export 290 MMT of Urea, earning an export revenue of $130 billion.
  iii. In the LCP, the Urea subsidy in 2050 is projected to be 65% lower than the BAU. The cumulative savings in subsidy during the 2025-50 period between BAU and LCP is a staggering $230 billion.
  iv. Under the LCP, GHG emissions in 2050 are projected to be 64% lower than BAU and less than half of the current emissions. The reduction in cumulative GHG emissions during 2025-2050 between the BAU and LCP is close to 1938 MMT CO_2e. Even at an average carbon price of $150 per tonne of CO_2 (likely a significant underestimation), the savings in GHG emissions can be monetised to a value of $290 billion.
  v. The reduction in Urea consumption also means a significant decline in nitrate pollution of groundwater and surface water bodies, along with improvements in soil health and agricultural productivity. The cost of nitrogen pollution of water due to Urea use in India in 2022 can be estimated at $29 billion. In the BAU scenario, this cost is projected to rise to $37 billion

in 2050. However, in the LCP, the cost of water pollution can be reduced by 60% in 2050 compared to the BAU scenario. The cumulative savings in health and ecosystem costs during the 2025-50 period in the LCP over the BAU is estimated at $315 billion.

vi. There is a clear economic case for moving to a Low Carbon Pathway for the Urea sector. The total environmental and economic benefits amount to approximately $985 billion. This is also an underestimation as air pollution and land degradation costs have not been included.

8. A Green Urea Mission

India has one of the most ambitious programmes to foster the growth of Green Hydrogen. The National Green Hydrogen Mission (NGHM) aspires to make India the global hub for the production, usage, and export of Green Hydrogen and its derivatives. With a target of 5 MMT of Green Hydrogen by 2030, the government has allocated ₹19,744 crore (approximately $2.5 billion) until 2029-30 to support this mission.

However, despite being the second-largest consumer of hydrogen after oil refineries, the Urea sector is not a priority in the NGHM. The mission prioritises sectors such as steel, transport, and shipping, not Urea.

But Urea manufacturing is the most natural fit for the NGHM as the technology to produce Green Urea from Green Hydrogen is available and established. In addition, our modelling study indicates that the cheapest way to produce Urea in India is through the Green Hydrogen route.

However, the industry will not move to Green Urea as it is highly controlled, has low profitability, and lacks incentives to innovate and modernise. The only way forward is to decontrol the sector and allow companies to compete in the market. Complete decontrol of Urea is possible if all subsidies are directly given to farmers through the Direct Benefit Transfer (DBT) route. This is not a new idea. In fact, the Shanta Kumar Committee set up in 2014, recommended that farmers be given direct cash subsidies, allowing the fertiliser sector to be deregulated. Farmers would be free to choose crops and fertilisers as per their requirements. The Urea industry, in turn, would compete in the market, bringing new technologies to reduce prices and improve efficiency.

To achieve the outcomes of the Low Carbon Pathway, apart from decontrolling the sector, the Government of India should launch a Green Urea Mission with the 2050 targets of:

i. Increasing the area under non-chemical farming to 30%.

ii. Improving nitrogen use efficiency by 30%.

iii. Reducing the proportion of Urea in nitrogenous fertilisers by 30%.

iv. Transitioning the entire Urea manufacturing sector to Green Urea.

The economic and environmental benefits of this transition are close to a trillion dollars.

01

Introduction

Since the Green Revolution, which kicked off in the 1960s as a response to India's low agricultural productivity and need to import food, the nation has relied on chemical fertilisers to provide the nutrients necessary for higher crop yields. In particular, the High Yielding Varieties (HYV) of seeds that undergirded this revolution in techniques of agricultural production respond best when used alongside the application of chemical fertilisers[1].

As a result, the annual consumption of chemical fertilisers in terms of key constituent nutrients - Nitrogen (N), Phosphorous (P_2O_5) and Potassium (K_2O) - has increased by 27-times — from 1.1 Million Metric Tonnes (MMT) in 1966-67[2], the beginning of the green revolution, to 29.84 MMT in 2022-23[3]. In parallel, the average consumption per hectare has increased by 20-times — from less than 6.99 kg in 1966-67[4] to 141.2 kg in 2021-22[5]. Consequently, total food grain production in India grew approximately 4.5-times from 74.23 MMT in 1966-67[6] to 329.7 MMT in 2022-23[7].

Nitrogen is arguably the most important nutrient in the NPK group. Phosphorous affects a plant's ability to adequately produce, use, and store food, while potassium influences the quality of fruit and seeds as well as its ability to resist disease. Nitrogen, on the other hand, forms a part of every protein cell in the plant, thus being crucial for the size and abundance of foliage, structure of stems and shoots, quantity, and nutritious value of the yield[8]. As such, nitrogen deficiency is more visible, and becomes immediately apparent to a farmer, while deficiencies in phosphorus and potassium might only be apparent if diseases attack the crop or in the ill health of seeds used to propagate the next generation. However, since most HYV seeds are incapable of producing viable offspring anyway, this issue is less notable. Further, India's soils are chronically nitrogen-deficient, with 98.4% of sampled agricultural soil displaying high to medium deficiency as per the test data from soil health card conducted during 2015-16 to 2018-19[9].

In 2022-23, Urea accounted for 56% of all fertilisers and close to 80% of the nitrogenous fertilisers used in India.

Consequently, nitrogenous fertilisers have received the most attention in India. In 2022-23, nitrogen provided 67.8% of all the nutrients in chemical fertiliser[10]. Of the various kinds of nitrogen fertilisers that are commercially viable, Urea is by far the most popular. This is due to a suite of reasons that shall be expounded later. For now, let it suffice to know that in 2022-23, Urea accounted for approx. 56% of all fertilisers and close to 80% of the nitrogenous fertilisers used in India[11]. In line with this trend, domestic Urea production grew from 0.14 MMT in 1966-67 to 28.5 MMT in 2022-23[12]. Today, India is the second largest producer and consumer of Urea in the world after China, using 35.7 MMT of the substance in 2022-23[13,14]. It is also the world's second-largest importer of Urea after Brazil[15].

1.1 The Challenges with Urea

As the primary fertiliser used in Indian agriculture, Urea is central to food security. Unfortunately, this exposes the country to two potential sources of risk. The first obviously arises from the cost of importing Urea since the ability to do so is dependent on international prices and availability. Import dependence can and is being addressed by scaling up domestic production to meet the deficit– the current government goal is to eliminate the need for Urea imports by 2025[16].

Second and more worrying is India's dependence on imported Natural Gas (NG), the chief input and most widely used feedstock in Urea production. Since NG is not produced domestically in sufficient quantities, the country's import dependence on this fuel is close to 50%. In 2021-22, India spent around ₹1 trillion or $12.02 billion on these imports[17]. Since 2013-14, approximately 30% of this NG was used by the fertiliser industry[18].

Finally, it is crucial to take into account the fact that Urea is highly subsidised by the government as a crucial component of food security and social welfare schemes. Thus, the changes in the market price of NG or Urea in international markets are borne directly by the Government of India at a massive cost to the national exchequer. In 2022-23, the Urea subsidy was earmarked at ₹153,353.5 Crore ($18.7 billion) but finally amounted to ₹168,692 Crore ($20.6 billion)[19]. For some context, this amount exceeds the entire annual budget of the State of Assam in 2023-24[20].

Overuse and Misuse of Urea

Compounding the massive cost of Urea is the fact of its current misuse and overuse. The recommended average ratio of NPK application on Indian agricultural lands is 4:2:1[21]. However, in 2022-23, the ratio of actual applications was 11.8:4.6:1[22].

Urea is typically applied through dry broadcasting. This practice is attended by the hope that timely rains or irrigation water will dissolve and carry the compound below the soil surface. If rain or irrigation water does not follow in adequate amounts, dry Urea decomposes into toxic Ammonia gas within 48 hours of application and dissipates into the atmosphere. On the other hand, too much water is likely to wash the Urea away and cause build-ups of nitrogen in water bodies.

One study suggests that the average efficiency of nitrogenous fertilisers being applied in India in terms of actual uptake by the target crops in question –Nitrogen Use Efficiency or NUE– in 2018 was 35%, as opposed to a North American average of 53%; certain European economies, report values closer to 80%[23].

Theoretically, if India achieves the NUE closer to that of North America, it would have translated into reduction in consumption of nitrogeneous fertiliser (as N) by 33% or 6.9 MMT in 2022-23. Considering only Urea, which accounts for 80% of nitrogeneous fertiliser, this improvement in NUE would translate into 12 MMT less Urea consumption in 2022-23 and $6.9 billion less Urea subsidy. In addition, this would have avoided about 60 MMT of Carbon Dixoide Equivalent (CO_2e) GHG emissions from Urea production and consumption.[24]

Urea use and manufacture were estimated to contribute about 172 MMT CO_2e emissions in 2022-23. This amounts to 4.3% of national GHG emissions and 21.7% of agricultural GHG emissions.

GHG Emissions

Beyond the financial burden and misuse/overuse concerns associated with Urea, the other issue with this fertiliser is the significant greenhouse gas (GHG) emissions its use and production entail. In production, emissions arise from the combustion of NG as a part of certain key processes as well as from the generation of power in Thermal Power Plants (TPPs). In consumption, the wastage mentioned above is primarily due to the volatilisation of Urea into Ammonia gas and then into Nitrous Oxide (N_2O). This is problematic because the global warming potential of N_2O is 298 times higher than CO_2[25]. As a result, Urea use and manufacture were estimated to contribute about 171 MMT CO_2e emissions in 2022-23. This amounts to 4.3% of national GHG emissions and 21.7% of agricultural GHG emissions[26].

1.2 Importance of Decarbonising Urea Sector

Agricultural GHG emissions have been historically resistant to change across the globe since certain processes, such as methane generation from livestock and the use of fertiliser, are an integral part of most modern agronomic systems. Addressing the source of more than 20% of India's agricultural emissions, i.e., those from Urea, thus represents an excellent starting point in the larger endeavour to decarbonise agriculture. This would also be a pivotal step towards achieving India's Net Zero commitments, which are to be realised by 2070.

Decarbonising the Urea industry has the potential to provide further benefits as well. Since decarbonising the production of Urea involves the delinking of Urea production from its reliance on NG, this insures India against the risks of being dependent on imported NG – namely price fluctuations and the uncertainty of availability. As such, this undertaking contributes towards ensuring the nation's energy security as well as food security by ensuring that Urea would continue to be available even if natural gas suddenly was not.

Finally, optimising Urea use will ensure higher NUE, lower soil and water pollution, higher food production and reduce the cost of subsidy. A lower subsidy outlay would save the national exchequer a huge amount of funds that could be used for other purposes. If spent on subsidising alternative fertilisers, this could go a long way towards addressing the imbalance of nutrient use in Indian agriculture and the consequent deterioration of soil health.

Decarbonising the Urea industry has co-benefit of energy and food security, as well as lower soil and water pollution, and reduced burden of subsidy.

1.3 The Study

This study approaches the solutions to the above-mentioned challenges from two distinct angles– Demand-side and Supply-side interventions. The first is by projecting Urea consumption up to 2050 through an analysis of six scenarios. Each of these considers different business interventions, policy mandates, and environmental conditions that could influence future demand. Effectively, each scenario represents different levels of concern towards optimising India's demand for Urea.

This is followed by a consideration of how India's domestic Urea manufacturing industry can be decarbonised while still meeting national requirements in the most cost-effective manner. This supply-side modelling is undergirded by a detailed analysis of each of the currently operating Urea manufacturing plants. Different production pathways –that produce Grey, Blue and Green Urea, respectively- are considered for each to project the levelised cost of Urea production up to 2050. Our findings show that the production of Urea without fossil fuels inevitably leads to massive savings, even when factoring in the required additional investment. Thus, our supply-side analysis highlights optimal pathways to producing Urea cost-effectively while eliminating the associated GHG emissions from production.

Finally, these demand-side and supply-side modelling exercises are put together to develop a roadmap for decarbonising both the production and consumption of Urea in India.

The study has been devided into the following sections:

- Stocktake – Develop a clear understanding of Urea production, use, overuse, and government initiatives to optimise use, NUE, and GHG emissions during both manufacturing and consumption.
- Demand Side– Optimising Urea Use
    - » Identify realistic goals for improvements in the efficiency of Urea use.
    - » Identifying achievable targets for non-chemical farming systems that could further reduce the deficit between produced and required Urea.
- Supply Side– Develop a Net-Zero roadmap for Urea production under various demand and supply side constraints.
    - » Highlight the required technology transitions and estimate associated costs for developing Greenfield Grey, Blue and Green Urea.
    - » Model the levelised cost of production of Grey, Blue and Green Urea up to 2050 for all the existing plants, both as Brownfield and Greenfield deployments.
- Low carbon pathways – Outline pathways to reduce GHG emissions from Urea through demand and supply-side management.

Decarbonising the Urea industry in India –which works in concert with the National Green Hydrogen Mission, Energy Efficiency targets under the Perform, Achieve and Trade (PAT) scheme, and Net Zero targets– is achievable, as shall be shown in this report. Doing so offers the opportunity for massive gains on financial, food security and environmental fronts.

The report presents an economically viable and environmentally sound strategy for the manufacture and consumption of Urea with minimal GHG emissions. Considering the growing demand for food production in India as its population continues to grow in terms of size and affluence, this strategy is crucial to India's food security and agricultural economy.

02

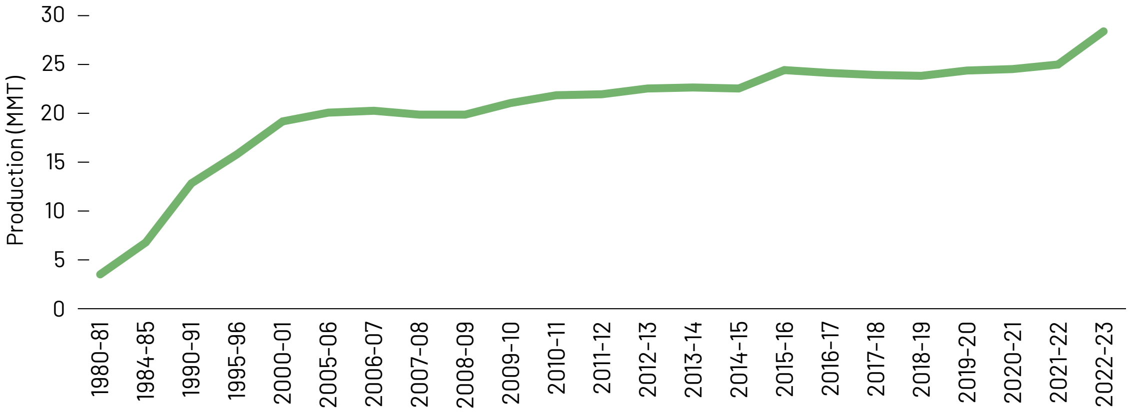
Urea in India

Due to a growing population, higher levels of affluence and evolving dietary habits, the demand for food in the country has increased since independence and will only continue to increase in the foreseeable future. Chemical fertilisers, especially Urea, have played an important role in enabling the increase in food production to meet this demand.

2.1 Production

Production of Urea in India started in 1960-61, and due to rapid growth in demand, domestic capacity for Urea production also grew from 0.011 million metric tonnes (MMT) in 1960-61[1] to 31.2 MMT in 2022-23[2].

Graph 2.1: Domestic Urea Production



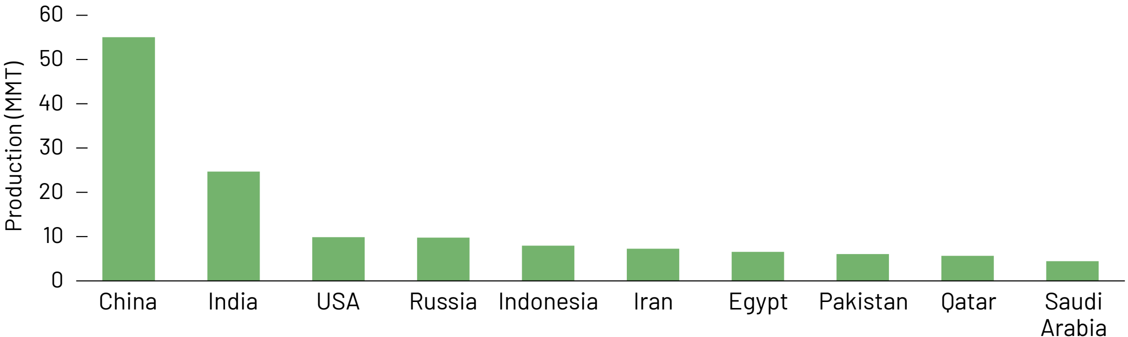
Source: Fertiliser Statistics Book 2022-23, Fertiliser Association of India

Urea production in India increased six-folds between 1980 and 2000. However, moderate growth rates have been observed in the years following this period. One of the key reasons for this is that no new Urea plants were established between 2000 and 2019. Notably, in 2015 an unusual rise in production was observed despite no new manufacturing units being commissioned. This surge was due to the introduction of the New Urea Policy (NUP), which allowed production at the reassessed capacity. The next significant rise in production was during 2021-22, as a consequence of commissioning new manufacturing units such as the Chambal Fertilisers and Chemicals Ltd. - Gadepan III, Ramagundam Fertilizers and Chemicals Limited, Hindustan Urvarak & Rasayan Limited - Gorakhpur, Barauni and Sindri Plants and Matix Fertilisers and Chemicals Limited, Panagarh.

Currently, India is the world's second-largest producer of Urea after China. However, there is a significant gap between the two; China's annual production in 2021 was 55 MMT, more than double of India's 24.7 MMT. Nevertheless, these two produce far more than other countries[3]. The USA ranks third and manufactures less than half of what India does.

India is the world's second-largest producer of Urea after China. However, there is a significant gap between the two.

Graph 2.2: Country-wise Urea production: 2021



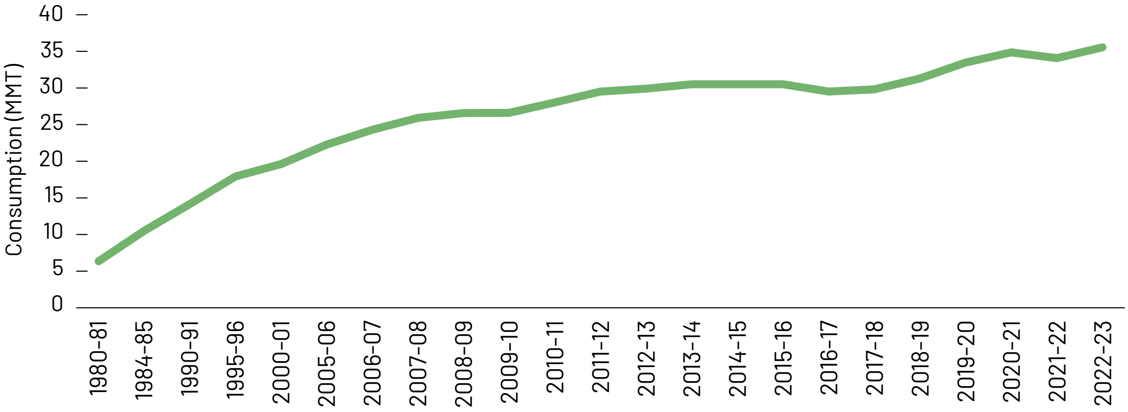
Source: Fertilizer Industry handbook-2022, Yara Fertilizer.

2.2 Consumption

Nitrogen is generally accepted as the most necessary nutrient for farming since most cropping systems are predicated on extracting parts of the plant where Nitrogen is concentrated– areas dense in plant protein. These include the foliage, fruits, shoots, seeds and so on[4]. As already discussed, Urea overwhelmingly dominates the fertiliser market in India, accounting for 80% of all nitrogenous fertilisers.

Urea consumption in India has increased consistently since its introduction in the country. The consumption has grown from 6.2 MMT in 1980 to 35.7 MMT in 2022-23, with a CAGR of 4.3% over the entire period. However, this growth was fastest in the period 1980-2000, when Urea consumption increased at 5.9% anuually. Urea consumption has since stabilised to reach an annual growth rate of approximately 2.8% in the past two decades.

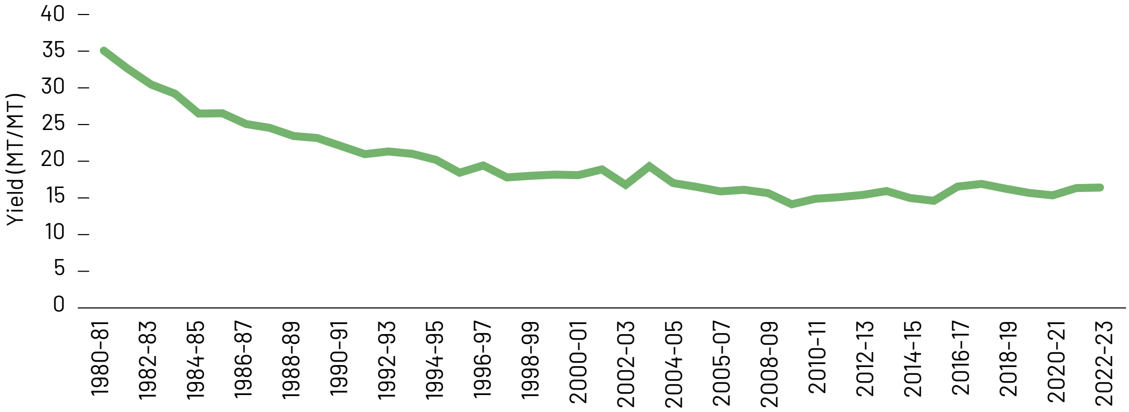
Graph 2.3: Domestic Urea Consumption 1980-2023



Source: Fertiliser Statistics Book 2022-23, Fertiliser Association of India

The relationship between the nitrogenous fertiliser consumption and foodgrain production indicates that the use of nitrogenous fertiliser (and even the total nutrients as NPK) in India has crossed a point of diminishing returns. For instance, the total foodgrain production per unit nitrogenous fertliliser consumption (as N) has more than halved in the last 40 years — from 35.2 MT/MT in 1980-81 to 16.3 MT/MT in 2022-23.

Graph 2.4: Foodgrains per unit nitrogenous fertiliser consumption

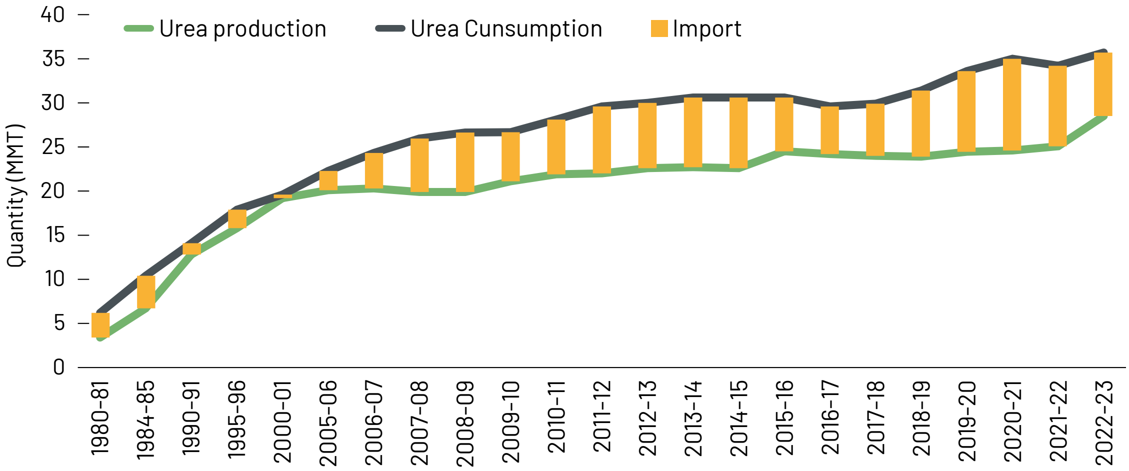


Source: iFOREST analysis

2.2.1 Urea Import

India has historically been dependent on Urea imports. However, after 2000-01, the imports have increased, ranging between 5 and 10 MMT for most of this period. Recently in 2020-2021, imports peaked and reached almost 10 MMT. The volume of imports is expected to fall in coming years due to the commissioning of six new plants from 2019-22 and the consequent expansion of domestic production capacity. Overall, the current import dependence is about 20%.

Graph 2.5: Urea imports 1980-2023

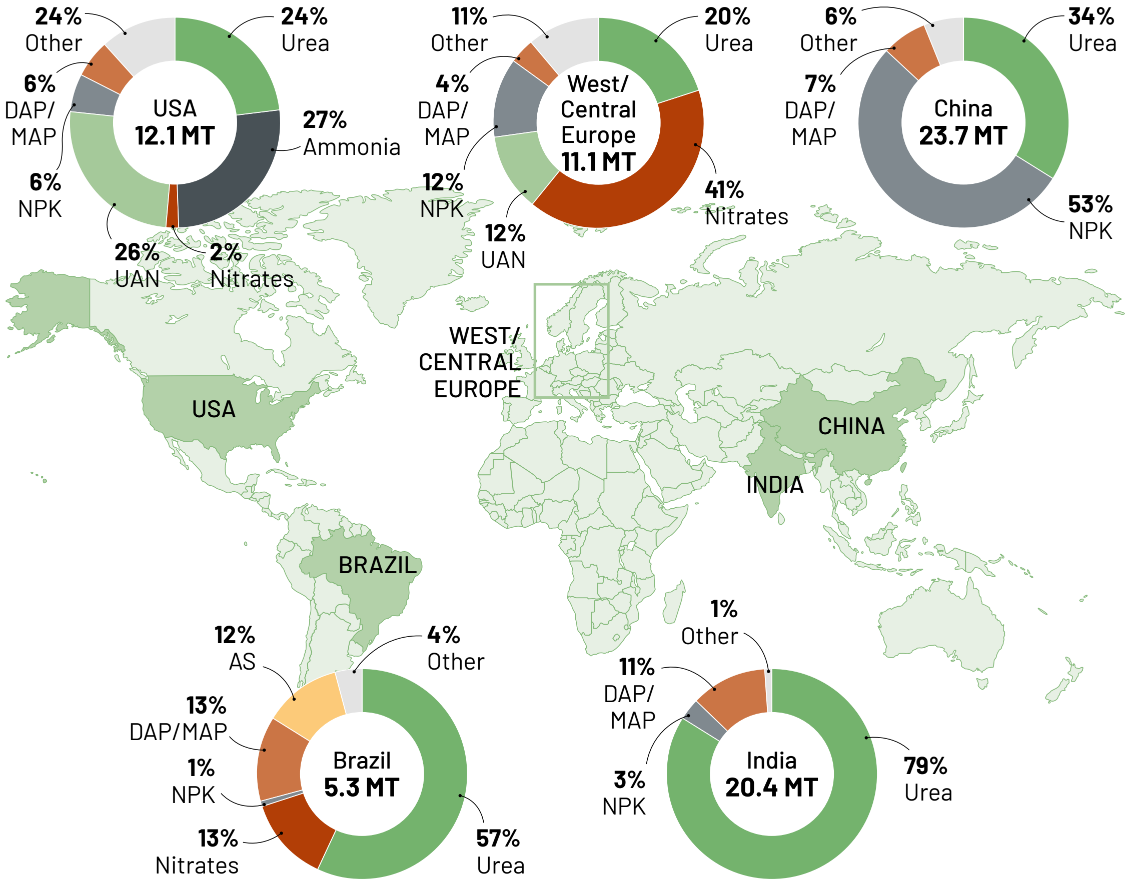


Source: Fertiliser Statistics Book 2022-23, Fertiliser Association of India

2.2.2 India Consumption vs Global Consumption

The rest of the world does not show the same enthusiasm for Urea over other nitrogenous fertilisers that India does. In most countries, Urea only provides between 24% and 34% of total nitrogenous fertiliser. Even Brazil, which ranks second after India, is a full 22% behind India's 79% market share that Urea occupies.

Map 2.1: Use of Different Nitrogen Fertilisers Across Economies



Source: Fertilizer Industry Handbook 2022, Yara Fertilizer

As such Indian agriculture clearly has an unusually high dependence on Urea– most other major fertiliser-consuming nations use a mix of various products to meet their N_2 requirements. The other products used include both complex (DAP, NPK, MAP) and straight (Ammonia, UAN, Nitrates) fertilisers.

2.2.3 State-wise consumption of Urea

Urea consumption in India is very uneven across regions and states. A few consume the lion's share while others use very little. The reasons behind this uneven consumption are:

1. Land available for farming is different across states, as certain states devote a greater share of their total land to farming, and each state's size is also not uniform.
2. Regional variations in climatic and soil conditions. Certain regions might contain soil with more available N_2 in the soil.
3. Prevailing agricultural practices. Certain communities have a greater preference or a stronger tradition for farming without the use of chemical fertiliser.
4. Policies of state governments for promoting non-chemical/ organic farming. For instance, hilly states, in particular, have concerted government programs to encourage Organic farming systems that discourage the use of chemical fertilisers.

Indian agriculture clearly has an unusually high dependence on Urea– most other major fertiliser-consuming nations use a mix of various products to meet their N_2 requirements.

Table 2.1: State-wise Urea Sales

Zone/State	Sales (MMT)		
	2012-13	2022-23	CAGR
EAST			
Bihar	2.10	2.20	0.46
West Bengal	1.39	1.41	0.16
Odisha	0.53	0.56	0.63
Assam	0.26	0.36	3.23
Jharkhand	0.20	0.25	2.36
North-East	0.05	0.06	4.00
East total	**4.52**	**4.84**	**0.68**
NORTH			
Uttar Pradesh	6.26	7.52	1.86
Punjab	2.84	2.94	0.34
Haryana	2.03	2.05	0.08
Uttarakhand	0.25	0.21	-1.53
Jammu and Kashmir	0.14	0.16	1.06
Himachal Pradesh	0.07	0.07	1.31
North total	**12**	**13**	**1**
SOUTH			
Andhra Pradesh (Including Telangana)	2.85	3.40	1.78
Karnataka	1.45	1.82	2.33
Tamil Nadu	0.93	1.00	0.75
Kerala	0.14	0.11	-2.10
South total	**5.40**	**6.35**	**1.63**
WEST			
Maharashtra	2.29	2.75	1.84
Madhya Pradesh	1.89	3.24	5.53
Gujarat	1.92	2.47	2.53
Rajasthan	1.85	2.52	3.16
Chhattisgarh	0.71	0.84	1.75
West total	**8.70**	**11.82**	**3.11**
All India total	**30.20**	**35.99**	**1.77**

Source: Urea sales in India, Fertiliser India

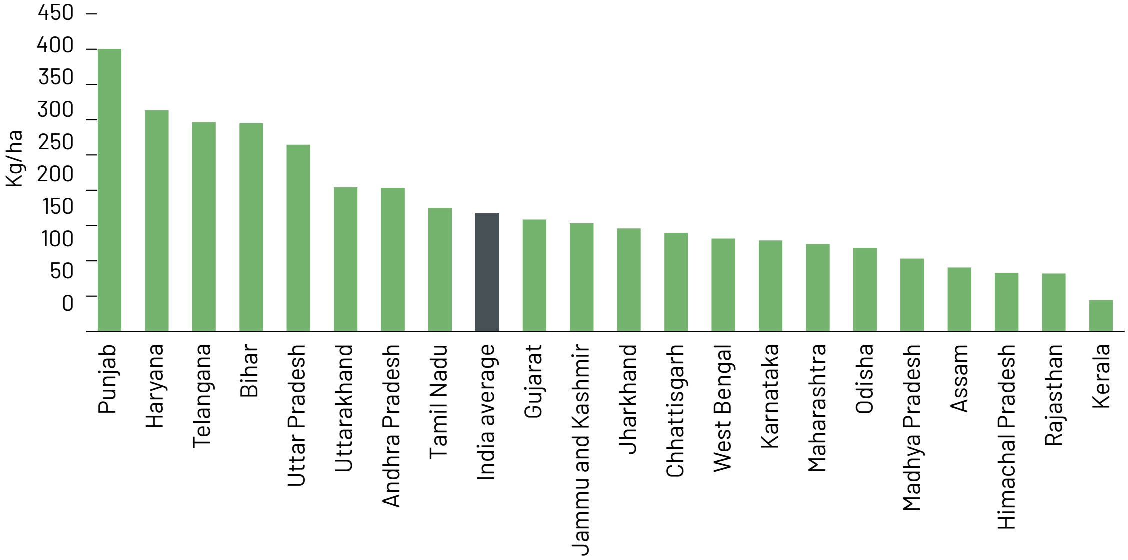
During the last decade, around 89% of Urea used in India was consumed by just 12 states[5] – Uttar Pradesh, Punjab, Madhya Pradesh, Maharashtra, Rajasthan, Gujarat, Bihar, Haryana, Karnataka, Andhra Pradesh, West Bengal, and Tamil Nadu in descending order of consumption. The remaining 11% is consumed by the other 24 states and UTs of India.

While most states have seen a growth in Urea consumption over the last decade, a few have also shown a decrease. Of the states that have reduced Urea consumption, except Kerala and Uttrakhand, most are minor consumers.

2.2.4 Urea Use Intensity

This was calculated by considering the Gross Sown Area in each state alongside the Urea consumption of the state in question for the year 2021-22[6]. The intensity of Urea consumption in India varies significantly between regions. This is likely due to differences in the intensity of farming practices, the duration for which the land in question has been under intensive agriculture, soil ecology and intrinsic fertility. Fertiliser consumption also varies with crop patterns and the crop rotation combination[7]. For instance, the three-crop-a-year rice-wheat systems along the Gangetic Plains are some of the most nutrient-intensive cropping systems in the world. The graph below shows Urea consumption intensity in (kg/ ha) for the year 2021- 22 for major Urea-consuming states.

Graph 2.6: Average Urea Use per Hectare of Farmland



Source: Fertiliser Statics book 2021-22, FAI, iFOREST analysis

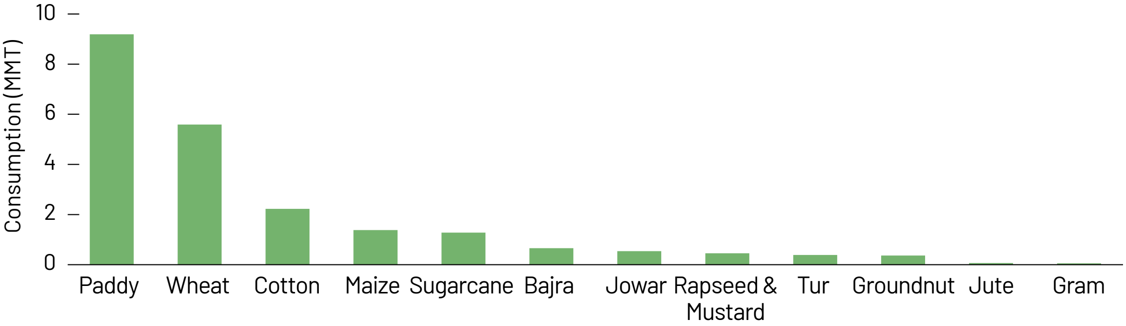
The Urea use intensity in India is highly skewed and ranges from 44.5 kg per ha in Kerala to 400.4 kg per ha in Punjab. The National average for 2021-22 was 166.9 kg/ha. Eight out of the considered 21 States in this list are ahead of the National average. Punjab is at the top of the list by quite a margin averaging 2.5 times more than the country's average. Next are Haryana, Telangana and Bihar, all of which are close to 300 kg/ha. On the flip side of things, States such as Assam, Rajasthan and Kerala are using less Urea than the Indian average. States that are missing in the above graph, such as the hilly Northeastern states, have negligible Urea consumption.

Urea consumption intensity in India varies significantly between regions, likely due to differences in farming practices, cropping pattern, soil ecology, and intrinsic fertility.

2.2.5 Crop-Wise Urea Consumption

Crops require different nutrients in varying quantities. The quantity of nutrients required also depends on the region where they are planted, the season of farming (Rabi/ Kharif), the crop rotation and health of the soil, etc. The latest data available for crop-wise Urea consumption is for the year 2016-17. This data shows that Paddy and wheat are the most Urea-consuming crops in India, collectively accounting for nearly 50% of India's total consumption.

Graph 2.7: Urea Consumption Across Crops



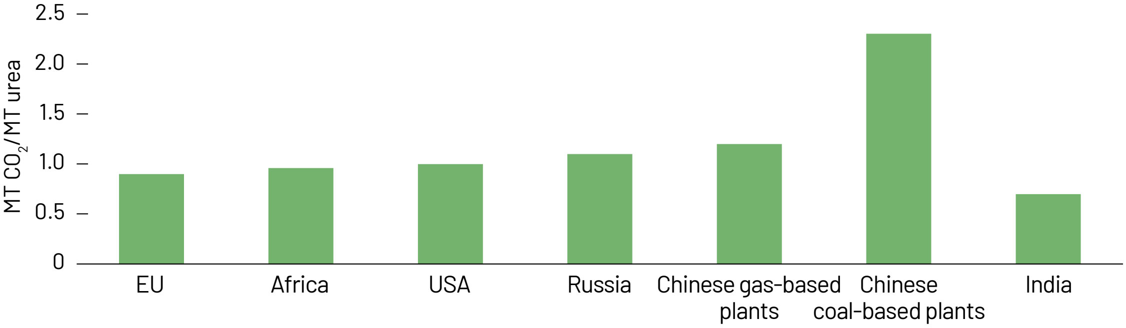
Source: Source: All India report on Input Survey 2016-17[8] and Agricultural Statistics at a glance 2018[9]

Cotton, maize, and sugarcane are the next most Urea-consuming crops, collectively consuming around 17% of the total. Other plantation crops, grains, oil seeds, etc., consume the rest.

2.3 Life cycle emissions

As alluded to earlier, Urea has a very high associated carbon cost. A large amount of Carbon Dioxide (CO_2) emission takes place in the production process. Urea is produced from Ammonia which in turn is produced from a feedstock of hydrocarbons (natural gas or naptha or coal). Each part of this process is associated with significant carbon costs. Further, the generation of electricity at captive power plants (CPPs) and/or purchase of electricity from the grid for the manufacturing of ammonia and Urea also contributes to emissions, as these have historically been mostly coal-based although renewable power is becoming more widely available. Overall, in India, an average of 0.7 MT of CO_2 equivalent (CO_2e) is estimated to be emitted for each MT of Urea during the production stage.[10] This is far better than the average emissions across the globe. In the EU's 27 countries, the emission rate is 0.9 MT CO_2e/ MT Urea produced, in the US it's 1 MT CO_2e/MT and Chinese gas-based plants emit 1.2 MT CO_2e/ MT Urea produced.

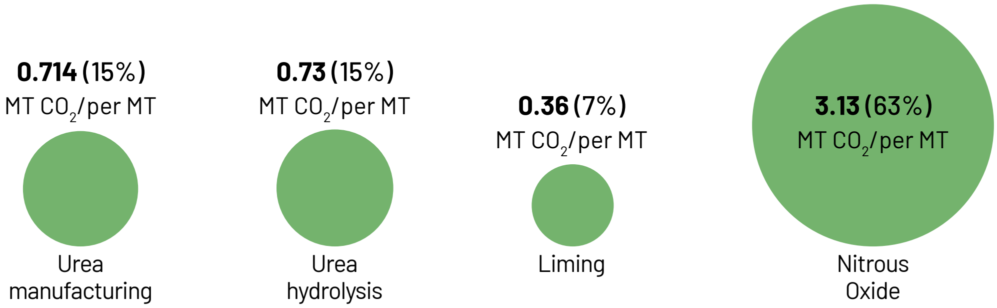
Graph 2.8: CO_2 emissions intensity of Urea production



Source: Green rating project 2018-19, Center for Science and Environment

However, emissions from production constitute only a small part of the lifecycle GHG emissions from Urea. The bulk of emissions come from the use of Urea in agricultural fields particularly during Urea hydrolysis (0.73 MT of CO_2 per MT Urea consumed) and liming (0.36 MT of CO_2 per MT Urea consumed)[11]. In addition, the use of Urea also gives rise to emissions of Nitrous Oxide (N_2O), which is a highly potent GHG. Applying a tonne of Urea leads to N_2O emissions equivalent to 3.13 MT CO_2e. Thus, GHG emissions beyond the plant gate total 4.22 MT CO_2e per MT of Urea consumed, which is six times the average GHG emissions from the production plant.

Graph 2.9: Lifecycle GHG emissions from Urea



Source: Carbon Footprint Reference Values, Fertilisers Europe

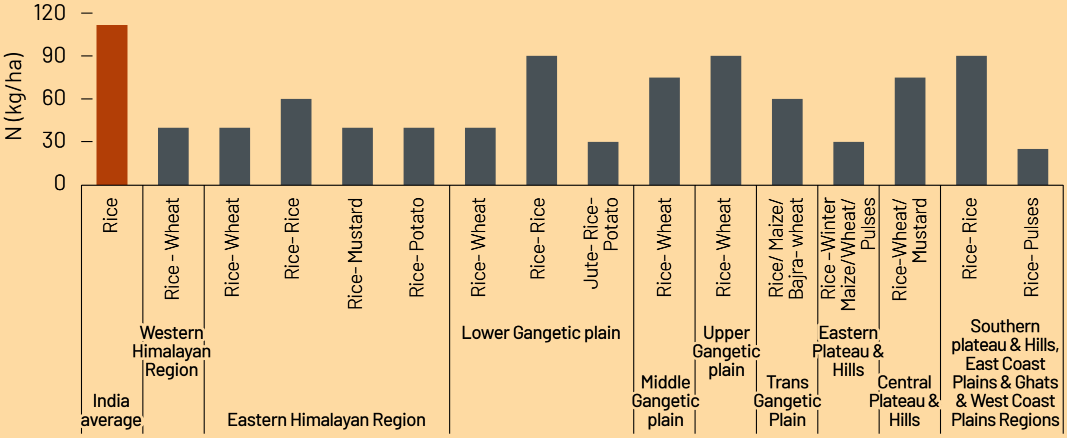
Given the scale of GHG emission contribution in manufacturing and application of artificial/synthetic nitrogen fertiliser, deep decarbonisation of the fertiliser industry is imperative. However, potentially even more important is addressing the post-application emissions from Urea through behavioural changes that ensure that Urea is applied through best practices.

OVERUSE OF UREA

The Indian Council of Agriculture Research (ICAR) has developed an Integrated Nutrient Management (INM) package that recommends the optimal amounts of fertilisers needed for different regions and cropping systems across the country. The INM package also considers various crop combinations on the same land to arrive at the nutrient needs of various crops in terms of N, P, and K.

Comparing the recommended dosage of nitrogen in various scenarios for different crops with the actual nitrogen provided to those crops, it is found that in most cases, the quantity of nitrogen applied is significantly more than the recommended quantity. The graph below considers the example of rice, which is the most widely produced crop in India as well as that attended by use of the most Urea.

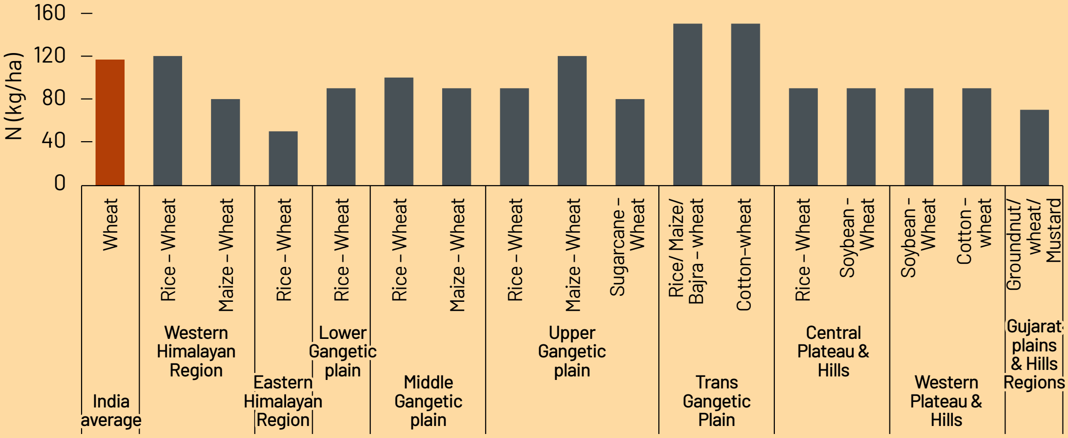
Graph 1: Recommended Nitrogen Consumption in Rice vs. Actual Consumption



Source: Recommended Dosage of Fertiliser, ICAR and Fertiliser Association of India

The actual consumption of N in kg per hectare in the cultivation of rice is much higher when compared to the recommended consumption in any scenario of region, season, or crop combination. In only very few scenarios, such as Rice-Rice and Rice-Wheat in certain regions, the recommended amount of nitrogen appears to be close to the amount being applied. Similar trends are observed with crops such as sugarcane, maize cotton etc. The only exception to this is in the case of wheat, where it is found that the applied quantity of nitrogen is regularly close to the recommended amount. This data gives a clear picture that nitrogen nutrient is overused in India.

Graph 2: Recommended Nitrogen Consumption in Wheat vs. Actual Consumption



Source: Recommended Dosage of Fertiliser, ICAR and Fertiliser Association of India

2.4 Government Policies for Optimising Consumption

It is widely recognised that India's heavy use of urea has led to deteriorating soil health, reduced crop yields, and a decline in Nitrogen Use Efficiency to about 35% in 2018.

Government Policy towards Urea has shifted over the years from a wholesale endorsement of the substance over all other fertilisers to a slightly more muted enthusiasm recently. Although Urea sales are still highly subsidised so that farmers can access this key agricultural input, the government of India is taking steps to ensure that other important nutrients such as Potassium, Phosphorous and Sulphur are also available at prices affordable to farmers. There appears to be clear recognition in the country that Indian farming's love affair with Urea has led to deteriorating soil health, crop yields and decline in Nitrogen Use Efficiency (NUE) from 48% in the 1960s to approximately 35% in 2018[12].

In recent years, there has been a flurry of policies that seek to address this low NUE caused by the disproportionate use of Urea due to its artificially low price. The chief strategy for addressing this appears to be the optimisation of Urea use through the release of new products such as Neem Coated Urea, Sulphur Coated Urea (Gold Urea) and Nano-Urea as well as changing the sizes of bags and so on. Nevertheless, the demand for Urea grows unabatedly.

The Government Policies of recent years can broadly be categorised into three groups:

i. Urea Demand Rationalisation: These are attempts to address the overuse of Urea as caused by issues with the misapplication of Urea and its misuse due to low cost to consumers. Some of the policies in this group are listed below.

Table 2.2: Recent Policies Regarding Urea Demand Rationalisation

Policy	Jurisdiction (and Parent Program if applicable)	Date	Rationale
Neem Coated Urea	National	2015-present	Coating of neem on Urea slows down the rate of release of nitrogen besides acting as an insecticide and addressing losses through pest damage. Thus, it increases nitrogen use efficiency.
Reducing the size of Urea bags	National	2017	The weight of Urea bag was reduced to 45 kg in 2017 from the earlier norm of 50 kg. This was thought to be appropriate due to the improved efficiency of Neem Coated Urea which has replaced conventional Urea. According to a latest study by global consultancy firm, Microsave Consulting, this has brought down the consumption of nitrogen by 8% per ha.[13]
Nano Urea	National; by IFFCO (Indian Farmers Fertiliser Cooperative Limited)	2021	Nano Urea is a fertiliser that makes use of extremely small Urea particles in a liquid solution. The idea was that the higher surface area of nano-Urea, as compared to conventional Urea, would aid in absorption. However, its efficacy has been challenged.
Gold Urea	National	2023 (August)	It contains 37% nitrogen and 17% sulphur. The weight of the Urea bag has also been reduced to 40 kg from 45 kg. This innovative composition serves two primary purposes: bolstering soil quality and boosting nitrogen utilisation efficiency.

Source: iFOREST analysis

ii. Promotion of alternative nutrients (P, K and S, among others) and nitrogenous fertilisers: These are attempts to redress the disproportionately high use of nitrogenous fertilisers over all other kinds of nutrients. Some of the policies in this group are listed below.

Table 2.3: Recent Policies Regarding Promotion of Other Fertiliser Nutrients

Policy	Jurisdiction (and Parent Program if applicable)	Date	Rationale
Nutrient Based Subsidy	National	2010 and revised frequently	Fertilisers are provided to the farmers at the subsidised rates based on the nutrients (N, P, K & S) contained in these fertilisers. Also, the fertilisers which are fortified with secondary and micronutrients such as molybdenum (Mo) and zinc are given additional subsidy.
National Mission for Sustainable Agriculture (NMSA)	National	2014-15 to present	Focuses on improving Soil Health Management (SHM). It also aims to promote crop and location-specific sustainable soil health management. This is attempted by creating soil fertility maps that would inform macro and micro-nutrient management, judicious use of fertilisers and organic farming initiatives[14].
Soil Health Card	National	2015	Part of NMSA, these cards provide information to farmers on the nutrient status of their soil along with recommendations on the appropriate dosages of nutrients to be applied for improving soil health, fertility and, eventually yields. Under the Central Government's Soil Health Card Scheme Phase-I (2015-17), 10.74 crore cards were distributed, while under Phase-II (2017-19), 11.69 crore cards were distributed to farmers.

Source: iFOREST analysis

iii. Promoting Alternative (mostly Organic) Farming Regimes: Organic Farming refers to a set of agricultural practices centred around the belief that the use of synthetic chemical fertilisers and pesticides is unsustainable both ecologically and agronomically in the long run. Instead, organic fertilisers in the form of mulch, manure and compost are used to supply plant nutrients. Over time, these practices rejuvenate soil health and encourage the return of the beneficial bacteria, microbes, fungi and insects that constitute a healthy soil ecosystem. Healthy agricultural ecosystems are better able to deal with pests and diseases. Most studies agree that after an interim period of one to two years during which soil health recovers, organic farming provides better or at the least very similar yields to conventional farming[15]. Further, organic farmland tends to fare better during stresses from environmental conditions such as drought, retain water better, thus reduce the cost of and need for irrigation, and finally maintain the fertility and health of soil long term[16]. Globally agreed upon standards are used by National and International organisations to certify agricultural practices as Organic.

Organic farming involves agricultural practices that avoid chemical fertilisers and pesticides, using organic fertilizers like mulch, manure, and compost instead, to ensure long-term ecological and agronomic sustainability.

Table 2.4: Recent Policies Regarding Alternative Agriculture

Name of Policy	Jurisdiction (and Parent Program if applicable)	Date	Rationale
City compost with Market Development Assistance	National	2020	The policy aims to address two issues–to make use of the municipal solid waste generated in cities and consequently reduce Urea consumption by providing organic alternatives (compost). A Market Development Assistance (MDA) of ₹1,500/ MT in the form of a subsidy has been provided for compost manufacturers willing to market city compost made from city waste[17].
Paramparagat Krishi Vikas Yojana (PKVY)	NMSA	2015 to present	Uses a cluster approach to promote organic farming in India. Groups of small farmers usually centred around a village, are inducted into the program together to create organic farming clusters[18]. The scheme offers farmers Participatory Guarantee System (PGS) certification which would help them access knowledge about the proposed farming techniques and further access favourable markets. Additionally, registered farmers are helped to access organic inputs and the capacity to generate these inputs themselves. Assistance is also offered to establish vermicompost units[19].
Mission Organic Value Chain Development for North-East Regions (MOVCD-NER)	NMSA	2016	Another centrally sponsored scheme, its ambit is the hilly North-Eastern states of Arunachal Pradesh, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura, and Meghalaya. The program is oriented towards developing certified organic production in these regions– securing the entire supply chain and market access for producers by linking them with consumers[20].
State Schemes	Individual state-level programs	Different times	The best example is Natural Farming in Andhra Pradesh

Source iFOREST analysis[21,22,23,24,25,26,27]

CASE STUDY: NATURAL FARMING IN ANDHRA PRADESH

Of all Indian States, the Government of Andhra Pradesh has been the most proactive in promoting the adoption of alternative farming techniques.

As early as 2004-05, the state launched a program called the Andhra Pradesh Community-Managed Sustainable Agriculture under the management of the Rural Development Department of the government. Initially rolled out with the help of women's SHGs that were used to disseminate knowledge, the programme focused on the management of pests using non-synthetic chemicals[28].

In 2014, the program was expanded and placed under the control of a private company, Rythu Sadhikara Samsth (RySS), which functions as a parastatal agency of the Department of Agriculture[29]. Championed by Padma Shri Subhash Palekar, the revamped program went through a few iterations of names– Climate Resilient Zero Budget Natural Farming (CRZBNF), simply Zero Budget Natural Farming, Andhra Pradesh Zero Budget Natural Farming (APZBNF) to finally Andhra Pradesh Community-Managed Natural Farming (APCNF)[30].

Similarly, the practices recommended as a part of this program have also been refined over the years. At its core, the model is of community-based knowledge dissemination using certain 'expert' farmers (community resource person or CRP) who share their insights after having practised 'Natural Farming' techniques for significant periods. It is important to note that Natural Farming is not identical to Organic Farming, although the two rely on several of the same tenets. Certain Natural Farming practices, such as the encouragement of multi-cropping, integration of animal husbandry and horticulture, mulching, and preference for indigenous seeds, are staples of Organic Farming programs worldwide[31]. Others, such as the mandatory[32] use of patented formulations of Beejamrutham (BJM), Dravajeevamrutham (DJM) and Ghanajeevamrutham (GJM) are less universally accepted.

Box continued

As Certified Organic Farming is practised on about 2% of India's farmland at present, Natural Farming cropland in AP does not yet appear to be compatible with organic farming certification standards. The APCNF website reports that it has reached 6 million farmers and 8 million hectares[33]. NITI-Aayog reports that the program reached 7.5 million farmers in 2020-21 and that AP has 10.1 million ha of cropland in total. APCNF appears to dominate approximately 80% of AP's farmland.

Table 1: Urea Consumption and Food grain Production in Andhra Pradesh

	Urea sales (MMT)	Food grain production (MMT)	Productivity (MT/MT)
2016-17	1.4	10.37	7.4
2017-18	1.4	12.16	8.7
2018-19	1.4	10.84	7.7
2019-20	1.5	12.36	8.2
2020-21	1.6	11.31	7.1
2021-22	1.5	11.27	7.5

Source: Fertiliser Association of India, Agricultural Statistics at a glance and Department of Agricultre and Farmers Welfare

Since Natural Farming began to be popularised in Andhra Pradesh, the State has maintained a steady level of food grain production without significantly increasing Urea consumption.

03

Demand-Side Management

As shown in the previous chapter, the demand for Urea in India has grown steadily since the 1980s. However, in recent years the rate of growth has slowed. This reflects a potential saturation of demand for the fertiliser as well as the influence of recent government policy.

The following section will present the projections of the demand for Urea up to the year 2050. These are based on the research of the Fertiliser Association of India (FAI), a study by the Food and Agriculture Organization (FAO 2018) of the United Nations and iFOREST's own research.

The FAI suggests using a fixed growth rate based on historical trends of Urea consumption to project demand for 2050.

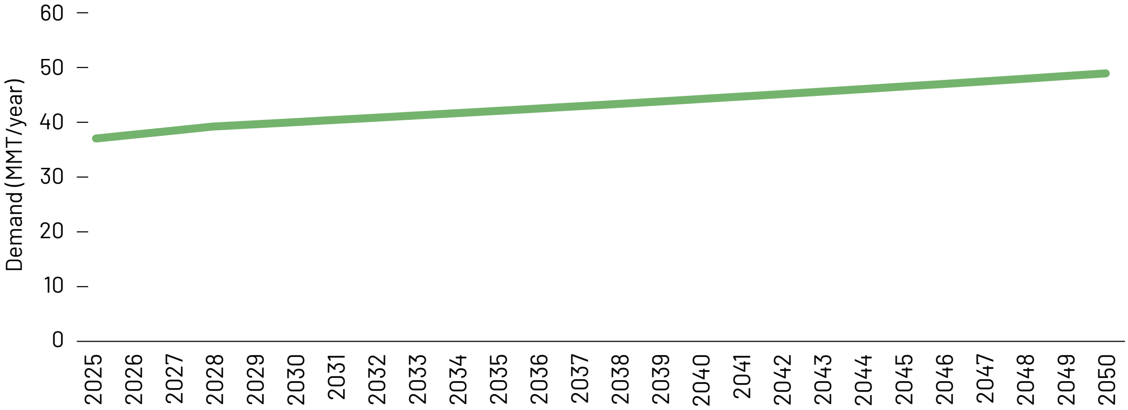
The FAO estimates crop nutrient requirements in the future based on factors such as food demand, technological changes, and the need to curtail GHG emissions. It has developed three distinct scenarios corresponding to different national and international policy orientations as well as environmental outcomes. The FAO thus considers more nuances in its estimate of Urea demand- its projections adapt to potential changes in political, sociological, technological, and environmental climates.

iFOREST has developed two scenarios based on food demand, prevailing practices, improvements in technologies, and a shift in agricultural practices towards coarse cereals and non-chemical farming.

3.1 Fertiliser Association of India

The FAI projects Urea demand based on a fixed growth rate of 2% for the first 5 years and 1% thereafter till 2050. Implicit in this projection is the assumption that the growth in demand for Urea in the next 25 years will be very similar to its historic growth in demand. By this projection, Urea demand will grow consistently till 2050 and will cross 49 MMT by 2049-50.

Graph 3.1: FAI Projection of Urea Demand



Source: Fertiliser Association of India

There are a few obvious shortcomings with FAI projections. These arise mostly from the fact that Urea in particular and nitrogenous fertilisers in general are currently overused. As mentioned earlier, India's NUE is on average a little more than half of that reported in Europe, USA and Africa[1], but less than half of that reported by the world best performers[2]. Improving this indicator while also addressing overuse would represent significant savings for both farmers and the government. The government policy is also supporting optimisation of Urea use. It is thus unlikely that India's domestic demand for this fertiliser will meet FAI projections.

3.2 Food and Agriculture Organization

The FAO uses national food production data and trends, considers climate impacts that are likely to affect the yields of crops in different climate zones and on different soil, explores different technologies of food production as well as changes in food preferences, examines the potential for conflict to disrupt progress, factors in the potential for gains and losses of agricultural land and finally adjusts for different socio-economic pathways that a region or state might take to develop multiple scenarios. By using a methodology that accounts for these varied and realistic influences that are likely to affect food production over the next 3-odd decades, the FAO's report released in 2018, offers an estimate that is better able to capture likely factors that will affect the production of different kinds of foodstuffs in different countries.

Towards this purpose, the FAO 2018 study makes use of climate models and scenarios adopted by the Intergovernmental Panel on Climate Change (IPCC) to predict different outcomes and pathways of global warming to the end of the 21st century. The climate models use iterations of two different scenarios – Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) – to predict GHG concentration and radiative forcing in the future.

The FAO 2018 study uses IPCC climate models and scenarios to to arrive at three consolidated scenarios for food production and fertiliser use.

SSPs represent changes in population, economic growth, education, urbanisation, and the rate of technological development that would affect future GHG emissions, providing a storyline of how the world could reach certain levels of warming. SSPs are closely tied to the RCPs, that provide different endpoints or outcomes without focusing on the paths taken to reach there. SSPs and RCPs are used by policymakers to plan for the type of future they hope to help create. It is configurations of these SSPs and RCPs that the FAO use to project food and nutrient demand till 2050.

Using a combination of different RCPs and SSPs, the FAO 2018 report arrives at three consolidated scenarios for 2050. These are the **Stratified Societies Scenario (SSS), Business as Usual (BAU), and Towards Sustainability Scenario (TSS)**. Each represents different degrees of commitment towards reforming food systems to be less environmentally costly, participating in international efforts to develop green technologies, and generally meaningfully participating in collaboration to address climate and sustainability challenges.

SSS represents a scenario where insular policy forestalls meaningful collaboration on Green Technologies and initiatives. Poor relations between nations cause each country to attempt to maximise independence in the production of essential commodities. Inequality thrives both across and within countries, with powerful elites taking control of Business and Political Agenda. These conditions contribute to maximising growth rates of food production and national GDPs, even though costs and damages from environmental instability rapidly accelerate.

Of the three scenarios measured, SSS projects the highest levels of divergence in agricultural systems across regions. Crop yields rise, and harvested areas expand significantly in High-Income Countries (HIC), while Low- and Middle-Income Countries (LMIC) struggle to maintain output due to higher climate change impacts. Additionally, farming remains input-intensive, driving up per unit costs of agriculture, and leading to reliance on imports to ensure food security in LMIC[3].

BAU represents a middle path, nominally towards sustainability but without a concerted effort towards mitigating the current global economy's reliance on GHG-producing activities. Income inequality within nations has reduced but continues to grow across nations. While investments in green energy are likely to increase, coal and petroleum are unlikely to be entirely phased out.

Under FAO's most ambitious scenario, Towards Sustainability Scenario, chemical fertiliser use is assumed to reach zero by 2050 worldwide.

Agronomically, the BAU scenario is characterised by higher growth in crop yields of nearly 30 per cent - in cereals, fruits and vegetables, and dominant crops of each region (such as soybeans in Latin American and Caribbean countries) - but lower growth in harvested areas - of around 18 per cent - compared to TSS. Despite higher crop yields, greater vulnerabilities to climate change are projected due to a lower emphasis on sustainable technologies. Limited access to sustainable technologies prevents harvested areas from growing as much as they would in the TSS scenario[4].

TSS represents an environmentally sound and socially equitable policy outlook. The gross world product (sum of all countries' GDP) in the TSS scenario is moderate, growing at 2.2 percent per annum from 2012 to 2050. However, it is more equitably distributed both within and across countries. Many SDGs are achieved, and some are exceeded.

Agricultural systems in the TSS scenario are characterised by moderate crop yield growth and substantial expansion of harvested area by around 25 per cent between 2012 and 2050. Wide implementation and further development of sustainable farming technologies drive crop yield growth. In addition, sustainable farming also enables higher cropping intensity, which drives the expansion of harvested area. The overall rise in production is relatively lower than projected in BAU or SSS. Notably, the R&D of sustainable farming techniques (and their wide adoption) are only made possible by the extensive public investment in these fields in this scenario[5].

As expected, the highest GHG emissions from agriculture are projected in the SSS scenario. Given that food preferences favour animal products and agriculture remain input-intensive, emissions will rise by 38 per cent between 2012 and 2050. This corresponds to CO_2 equivalent emissions corresponding with RCP 8.5 or a temperature increase of 5°C over the year 2000 by 2100[6].

Table 6 below outlines the different RCPs, SSPs, and SDGs associated with each of the three scenarios considered.

Table 3.1: RCP, SSP, and Associated Temperature Change

Scenario	RCP	SSP	Sustainable Development Goals									Temperature Change
			SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 10	SDG 15	SDG 16	Degrees Celsius Over 2000
TSS	4.5	SSP1	✓	✓	✓	✓	✓	✓	✓	Only 15.3	✓	2.5-3
BAU	6.0	SSP2/3	×	×	✓	✓	×	✓	✓	×	✓	3-3.5
SSS	8.5	SSP4	×	×	×	×	×	×	×	×	×	5

Source: Food and Agriculture Organization 2018

3.2.1 FAO Food and Nutrient Demand Methodology

FAO food projections across different scenarios are obtained by detailing currently available agricultural land, trends in productivity (including impacts of climate change, the degradation of land resources as well as the use of different agricultural techniques) and the ability of a Nation-State to bring more land under tillage. Depending on the combination of these factors that are predetermined by the combination of RCPs and SSPs detailed above, the food production of each polity varies across the three scenarios – TSS, BAU and SSS. For instance, the FAO's TSS scenario is predicated on reducing land use for livestock rearing and eliminating conventional chemical-intensive farming. However, it also presupposes achievements in sustainable farming technologies that come about because of massive investment in R&D in the field. SSS, by comparison, is predicated on the increasingly intensive use of chemical inputs in farming.

The projections for all three scenarios capture these nuances through the use of two quantitative models: FAO Global Agriculture Prospective Systems (GAPS) and FAO Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE).

FAO GAPS is a partial equilibrium model pertaining to the production and demand of food, agricultural commodities, and nutrition. Its projections are calibrated using food data from FAO Food Balance Sheets. FAO ENVISAGE, on the other hand, is a broader general equilibrium model which describes the entire economy and provides the framing for FAO GAPS estimates[7].

These projections for the evolution of food production over the years are then computed alongside average crop-wise fertiliser use data from the International Fertilizers Association for the years 2011, 2012 and 2013. 2012 was considered the base year by the FAO. Once extrapolated, this allowed the FAO 2018 study to estimate the total quantity of different nutrients that various scenarios will require. Since the ideal ratio of nutrient fertiliser application in India is 4N: 2P: 1K, this means that N_2 accounts for approximately 57% of all required nutrients[8]. To project N_2 requirements as per FAO scenarios, this share of N_2 was assumed to remain constant.

iFOREST has used nitrogen requirements under different FAO scenarios to project the demand for Urea. It has done so by assuming a second constant– namely, the percentage of N_2 supplied by Urea in the next 25 years. Since currently, 79% of India's nitrogen fertiliser needs are supplied by Urea, it is assumed that this will continue until 2030. Post-2030, the share of Urea will reduce and reach 60% by 2050.

The food production in India in 2050 across the three FAO scenarios varies significantly with maximum production in BAU and minimum in the TSS.

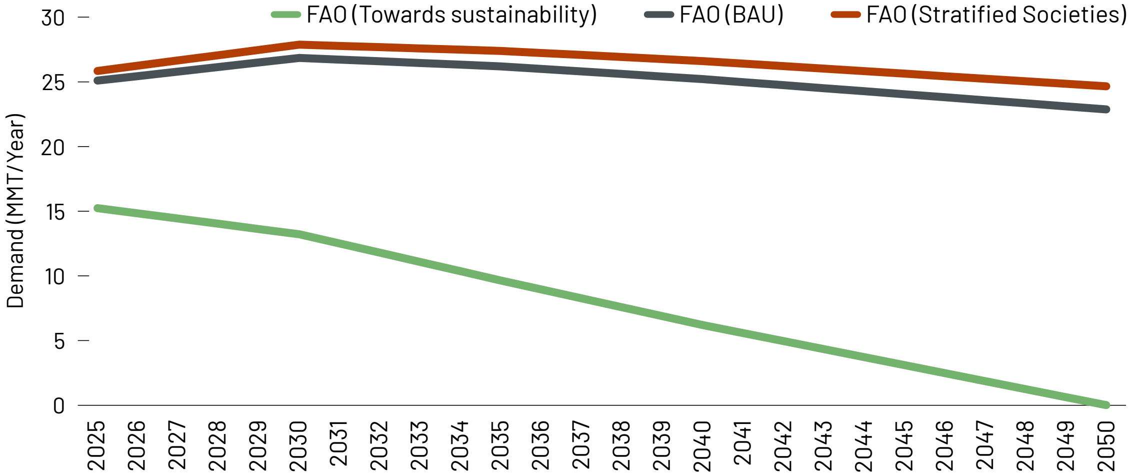
3.2.2 Urea Demand under FAO scenarios

The aggregate food produced in India in 2050 varies across the three scenarios with maximum production in the BAU and minimal in the TSS. The increased adoption of sustainable technologies projected in the TSS scenario lowers crop yields in comparison to the BAU and SSS scenarios. This is a somewhat pessimistic and strange prediction since ample research in 2023 already shows that sustainable agricultural practices such as organic farming offer comparable, if not superior, yields to conventional chemically intensive farming[9]. These alternative farming practices also demonstrate greater resistance to aberrant climatic conditions such as drought and flooding[10]. The enhanced resistance to climate change, as well as less intensive calamities due to curtailed emissions and temperature rise, means that food production in the TSS scenario should exceed that of at least the SSS scenario.

However, it is important to note that even the TSS scenario does not meet the Paris Agreement's goal of limiting global warming to 1.5 degrees Celsius by 2100. The TSS scenario causes a temperature rise of 2.5 to 3 degrees Celsius by 2100. At this scale of temperature increase, crop yields begin to decline. A temperature that is 1.8 degrees Celsius over ambient levels corresponds to a decrease in rice yields of 7-21%[11].

The calculated levels of estimated Urea demand indicate that about 24.6 MMT would be consumed in the BAU scenario by 2050. Note that this figure corresponds to only required levels of Urea consumption not accounting for losses to inefficiency or wastage, i.e., it pre-supposes no overconsumption of Urea. Urea demand in the SSS scenario indicates that around 23 MMT would be required by 2050. Given that chemical fertilisers are phased out in the TSS scenario, Urea demand will drop to zero by 2050.

Graph 3.2: FAO Urea Projections



Source: FAO data and iFOREST analysis.

Shortcomings with FAO projections

1. The primary shortcoming with the FAO projections is that the fertiliser data it has used is dated. By virtue of using 2012 as the base year from which food production values are extrapolated, FAO projections cannot account for trends in Urea consumption that have been seen over the last decade. As such, it becomes apparent from a consideration of the values that the starting point for Urea consumption in these scenarios (in the year 2025 above) is already quite at odds with historical projections. Essentially since in 2023, Urea consumption amounted to 35 MMT, it is unlikely that Urea consumption in 2025 will fall to anywhere close to 25 MMT.
2. In addition, the assumption that a move towards sustainability -as espoused in the TSS scenario- is predicated on the elimination of the use of chemical fertilisers is simply impractical in the context of developing countries. This is simply not feasible for countries like India, which still have large sections of their populations bereft of access to adequate quantities of food.
3. Finally, FAO data values are provided only for 2012, 2030, 2035, 2040 and 2050. As such, values for interim years have been extrapolated.

3.3 iFOREST

iFOREST has built two scenarios to project Urea demand by 2050 – Business-As-Usual (BAU) and Optimal. Both these scenarios are built around the fact that food production in India will need to grow at 1.5% per annum to meet the demands caused by growing population, increased per capita income and dietary changes. This goal has also been laid out in the Indian Council of Agricultural Research (ICAR) Vision 2050 document[12].

BAU Scenario: Under this scenario, there are no radical changes in the agriculture practice in the country. The improvements in productivity continues due to incremental changes in technology. There is no widespread use of organic or non-chemical farming. The Urea Response Ratio, calculated as tonnes of food grain produced per tonne of Urea consumption, will continue to improve at the past rate. The Urea Response Ratio in India has improved from 8.8 MT food grains/MT Urea in 2011 to 9.2 MT food grains/MT Urea in 2022. At this rate, the Urea Response Ratio in 2050 is projected to be 11 MT food grains/MT Urea.

The Urea Response Ratio is improving due to many factors, including changes in the types of crops being grown as well as government programs to enhance the efficiency of Urea use, such as reducing the size of Urea bags and new products such as Neem-Coated Urea.

Under BAU, the overall consumption of Urea, however, continues to increase in an attempt to meet the 1.5% annual growth in food production. The few regions that currently do use chemical fertilisers sparingly will be brought under the regime of intensive agriculture. Consequently, the demand for Urea will grow steadily through 2050. Such a route will naturally correspond with increased GHG emissions from the use of fertilisers in agriculture. Since it is unlikely that all the Urea consumed in this scenario is produced from greener feedstocks, this pathway also leaves India dependent on the import of fossil fuels. Urea demand in this scenario is approximately 45.3 MMT in 2050, similar to FAI projections.

Optimal Pathway reflects recent government and private sector efforts to decrease urea use, enhance agricultural productivity, and mitigate environmental pollution, while also addressing future demand and ground realities influencing urea usage.

Optimal Pathway: This scenario is built around the efforts made by the government and the private sector in the last few years to reduce Urea use, improve agricultural productivity, and reduce environmental pollution. It is also built to reduce GHG emissions from the agriculture sector. Certain key considerations and ground realities that are likely to influence the demand for Urea in the coming years and decades are also factored in. These are discussed below.

1. Demand Saturation – This scenario accounts for the fact that in major agricultural states, Urea is overused and, hence, has reached demand saturation. As the country's cultivated area is not likely to increase significantly, Urea demand in the country is also likely to reach the point of saturation soon.
2. Government policy towards improving Urea Response Ratio – The percentage of Urea that is actually contributing towards plant growth as opposed to being lost to the environment or wasted in other ways. This, too, is likely to lead to a reduction in the total quantity of Urea consumed. Initiatives such as Neem Coated Urea and Gold Urea, as well as educational outreach about proper Urea use through initiatives like the Soil Health Card are likely to contribute towards this endeavour.
3. Government promotion of alternate fertilisers – Further shifts away from intensive overuse of Urea are likely to come about as a result of Government incentives towards other nutrient fertilisers. The recent Nutrient Based Subsidy

(NBS) scheme has already encouraged the demand for historically underused fertilisers in Indian agriculture, such as Potassium and Phosphorous. As farmer spending on other fertilisers grows more balanced, this will further help bring down the artificially inflated demand for Urea.

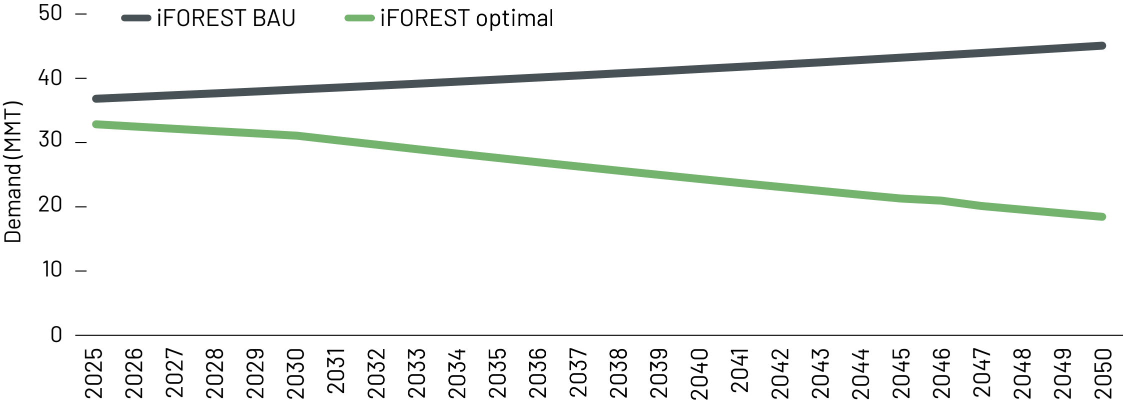
4. Government promotion of natural farming and organic agriculture – Alternative farming systems such as Certified Organic Farming, in particular, are predicated on not using synthetic chemical inputs. The government of India in recent years has clearly expressed the intention to improve the coverage of such farming regimes across the country[13].

Based on the above, the Optimal Scenario projects that by 2050:

- About 30% of India's agricultural land will come under the ambit of natural/organic/non-chemical farming.
- NUE will improve by 30% from 2023 levels by 2050. This would bring India's NUE closer to that enjoyed by regions such as North America (53%)[14], if not quite at the level that world leaders such as the Netherlands (70-80%[15]) enjoy. Optimising NUE and adopting alternatives to chemical fertilisers such as in organic farming, and growing less rice and wheat would contribute greatly towards achieving this.
- The share of Urea as percentage of nitrogenous fertliser reduces from 80% currently to 60% by 2050.

If these goals are achieved, Urea demand will fall from 35.7 MMT in 2022-23 to 18.2 MMT by 2050 while ensuring that India's food grain production improves to the required target.

Graph 3.3: iFOREST Projections of Urea Demand

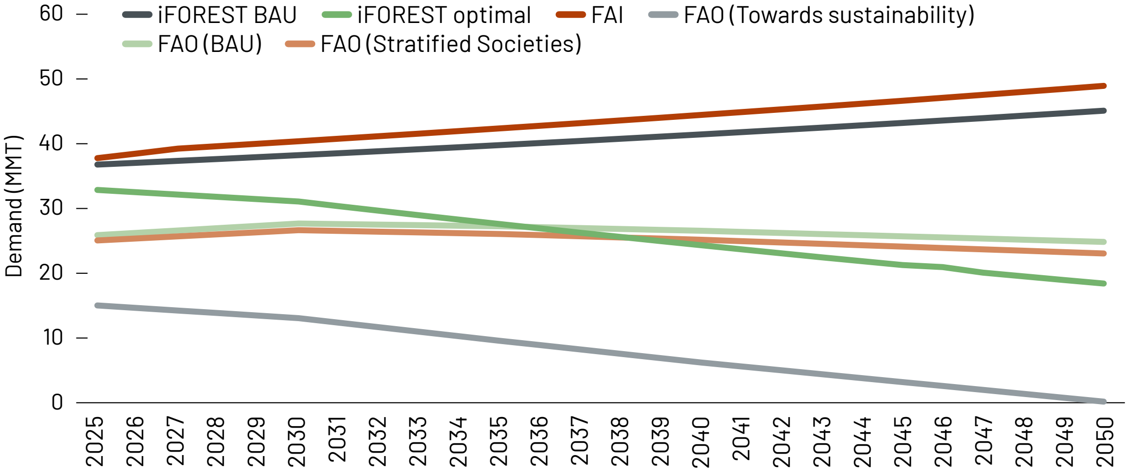


Source: iFOREST analysis

3.4 Comparison of Projections

The two highest-demand projections for Urea by 2050 are the FAI and iFOREST BAU. Under FAI, it increases at a steady pace and reaches 49 MMT. Next is the iFOREST BAU scenario, which follows the food demand projection by ICAR, population projection by 2050 and the Urea Response Ratio trend observed from previous years. This study projects Urea demand of around 45.3 MMT by 2050.

Graph 3.4: Comparison of Projections of Urea Demand



Source: FAI, FAO, iFOREST

The lowest demand scenario is FAO's TSS, which argues that by 2050, Urea demand will gradually decrease to zero. This projection is impractical for the Indian context and thus should not be considered for the reasons discussed in section 3.2.

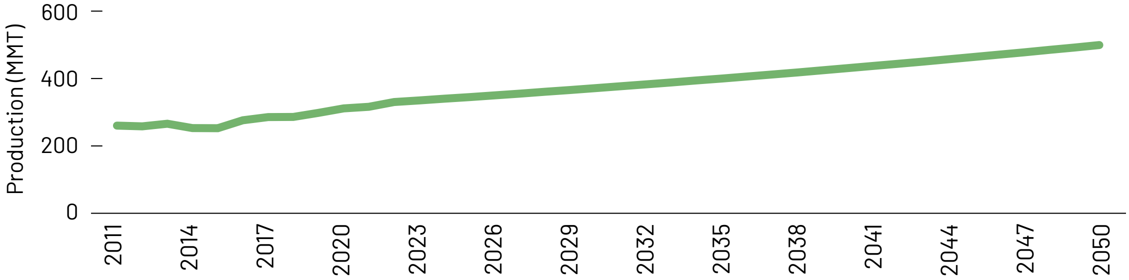
Then there are are two FAO projections – BAU and SSS. Both FAO scenarios show a moderate increase in consumption between 2025 and 2030; After 2030, Urea consumption is projected to decrease, albeit at a moderate rate. The results of both scenarios are very close to each other, i.e., 24.6 MMT and 22.85 MMT by 2050, respectively. But both these scenarios have been built using dated data. In addition, downscaling FAO's global model to country level is inappropriate. Nevertheless, they do provide a ceratin benchmark for national projections.

The iFOREST's Optimal Scenario projects Urea demand of around 18.2 MMT by 2050, as half of the current consumption. In this scenario, non-chemical farming area reaches 30% by 2030, NUE too enhances by 30% and the share of Urea in nitrogenous fertiliser reduces to 60%. All these improvements are in in congruence with the GoI policies and initiatives of many state governments. Considering this, iFOREST's Optimal Pathway has been considered as the most suitable demand-side scenario for India.

3.4.1 Optimal demand pathway

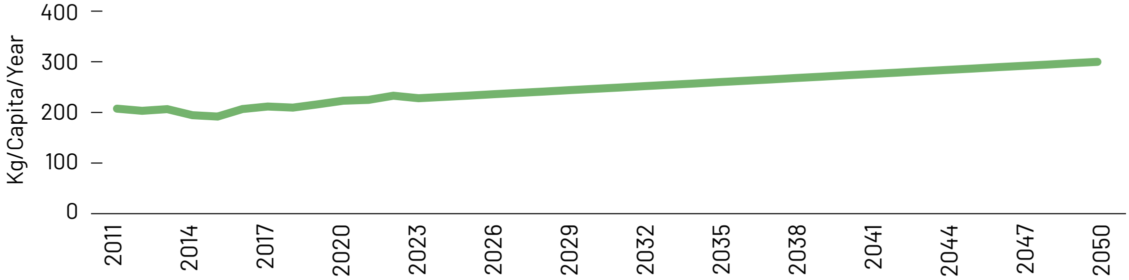
Under the optimal pathway, foodgrain production in India is projected to increase from 330 MMT in 2022-23 to 500 MMT in 2050-51. Per capita food availability is expected to rise from 230 kg per capita per year in 2022-23 to 300 kg per capita per year by 2050-51. Nitrogen demand is anticipated to decrease from 20.2 MMT in 2022-23 to 14.1 MMT in 2050-51. Correspondingly, Urea demand is projected to decline from 35.7 MMT in 2022-23 to 18.2 MMT by 2050. Greenhouse gas emissions from Urea use are expected to drop from 150 MMT CO_2e currently to 77 MMT CO_2e by 2050. It amounts to a per capita emissions of 0.05 MT (46 Kg) of CO_2e per year. This relatively small amount of emission can be easily sequestered through alternative means, including in India's forests.

Graph 3.5: Food Grain Production projection in Optimal Pathway



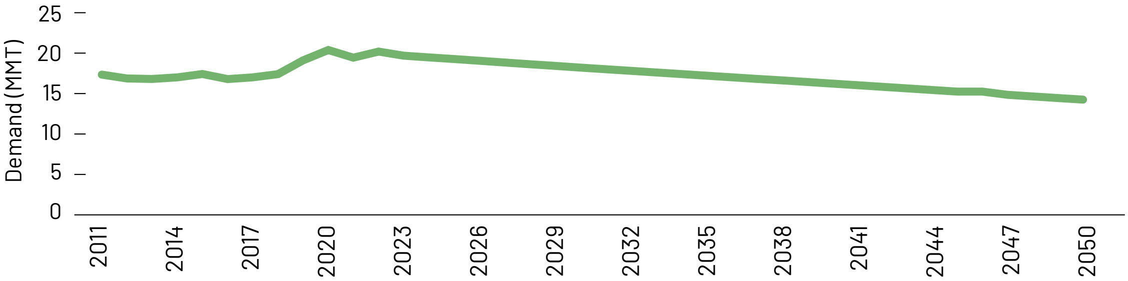
Source: iFOREST analysis

Graph 3.6: Per Capita Food grain Availability in Optimal Pathway



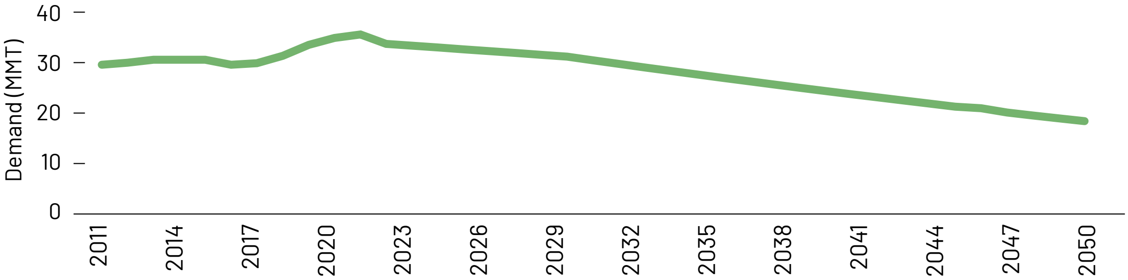
Source: iFOREST analysis

Graph 3.7: Nitrogen Demand in Optimal Pathway



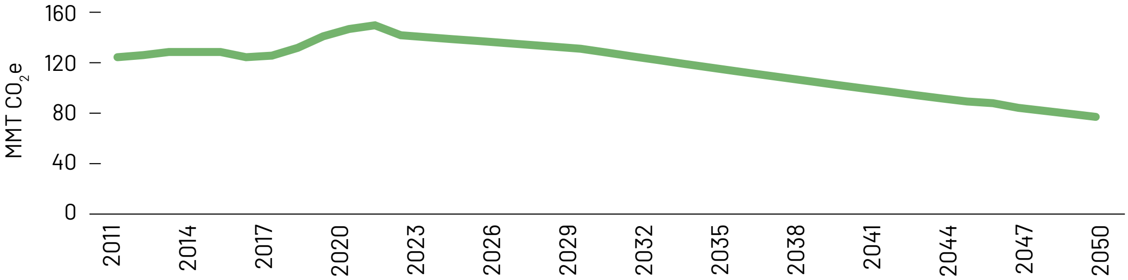
Source: iFOREST analysis

Graph 3.8: Urea Demand in Optimal Pathway



Source: iFOREST analysis

Graph 3.9: GHG Emissions from Urea Use in Optimal Pathway



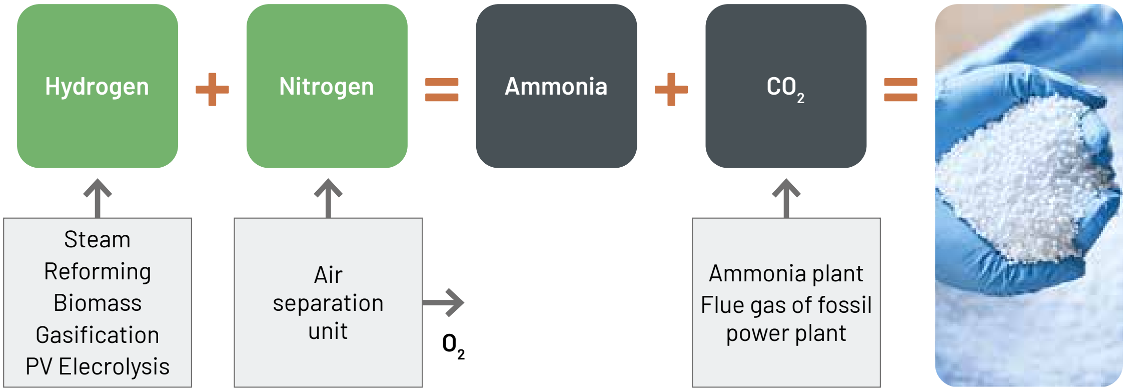
Source: iFOREST analysis

04

Supply-Side Decarbonisation

The process of making Urea (NH_2CONH_2) involves the production of Ammonia (NH_3) and then the reaction of Ammonia with Carbon dioxide (CO_2). The production of Ammonia requires access to significant amounts of pure Hydrogen (H_2) and Nitrogen (N_2). The sourcing of H_2 is the most challenging aspect of Urea production. Most commonly, it is obtained by the Steam Methane Reformation (SMR) process wherein Natural Gas (CH_4) is reformed to extract H_2 and CO_2. However, H_2 can also be obtained by electrolysis process. Similarly, CO_2 is generated during the SMR process itself or can alternatively be sourced from the flue gas streams of plants using fossil fuels through the use of carbon capture and storage (CCS) technology. N_2 is obtained through air separation technology.

Figure 4.1: Urea Synthesis Overview



Source: Multi-objective optimization of green urea production, Energy, Science and Engineering

In order to differentiate between distinct production technologies and their associated GHG emissions, a spectrum of colours is assigned to Urea. This spectrum has several colours, and the production pathways associated with each have slightly different emissions profiles. This report will restrict its concern to only three of these. They are:

- **Green Urea:** Made with renewable energy, it has zero CO_2e emissions during production. Here, H_2 is produced from electrolysis, N_2 from an Air Separation Unit (ASU) and CO_2 is sourced externally. It can be net negative in CO_2e emissions during production if the CO_2 used is sourced from those emissions that would otherwise have been released to the atmosphere. Viable sources for this include coal-based thermal power plants (TPP), cement, and steel plants.
- **Grey Urea:** Made using natural gas and conventionally generated electricity (either from the grid or captive TPPs). It has the highest GHG emissions. In this method, H_2 and CO_2 are produced from the steam reforming of NG, and N_2 is obtained from air.
- **Blue Urea:** This is usually made with a mix of renewable and non-renewable energy and inputs. A part of H_2 and electricity is produced using renewable energy, whereas the remainder is produced using NG. GHG emissions are much less in comparison to Grey Urea but are not zero. In this method, all the CO_2 produced during steam reforming and from the captive power plant is captured and utilised in the process of Urea synthesis.

The relative advantages of each of these technologies are described below.

Sourcing Hydrogen is the most complex process in Urea manufacturing. Presently, Hydrogen is produced by steam reformation of natural gas.

Table 4.1: Comparison of Production Pathways for Urea

Type	Process Description	Average Energy Consumption	Average CO_2-e emissions	Pros	Cons
Grey	• Uses non-renewable energy usually. • Makes use of Steam Methane Reforming (SMR) which uses NG as a feedstock to produce H_2 and CO_2.	• Total 5.7 Gcal/ MT of Urea Produced[1]	0.7 MT of CO_2 equivalent emissions per tonne of Urea produced[2].	• Proven technology • Low initial cost in present scenario	• GHG emissions are high • Dependent on NG, which is an imported commodity in India. • Operating cost fluctuates corresponding to the price of NG.
Green	• Uses renewable energy. • Uses electrolysis to split water into O_2 and H_2. This replaces hydrogen from SMR entirely. • N_2 is obtained with the use of ASU • N_2 and H_2 react to produce Ammonia. • CO_2 is sourced externally, thereby acting as a carbon sink.	• Total 5.4 Gcal/MT of Urea Produced[3]	Zero direct CO_2 equivalent emissions. It is even net negative since carbon is being sourced from polluters.	• Works as a carbon sink for other carbon intensive industries • Operating cost remains almost constant. • No dependence on imported NG.	• New technology, which is still in evolving stage. • High initial capital cost as compared to the Grey Urea plant, however, same will come down as the technology evolves. • Procuring CO_2 from external source and transporting the same is a difficult task.
Blue	• Uses some combination of renewable and non-renewable energy. • Blue Ammonia integrates carbon capture with SMR to minimize GHG emissions. • Usually also makes use of some percentage of Green H_2/Ammonia since in this system there tends to be an excess of CO_2 over other inputs. • Can lead to a reduction of almost all emissions from the Urea manufacturing process but is still dependent on the use and availability of NG.	• 5.8 Gcal/ MT of Urea Produced[4]	0–0.1 MT of CO_2 equivalent emissions per tonne of Urea produced[5].	• Scope 1 GHG emissions are reduced, as most of the Carbon dioxide is captured and utilized in Urea synthesis. • Plants manufacturing Grey Urea can be transformed in Blue Urea with comparatively low capital investment and short shut down time.	• High maintenance cost as more equipment is required. • This scenario is applicable for a shorter duration, until Green Urea technology gets evolved. After which Green Urea will be the preferred option. • Modification in existing system is required

Source: iFOREST analysis of IEA data and Industry Study.

4.1 India's Urea Industry

The Urea industry in India comprises 36 plants of varied sizes spread throughout the country. A significant number are concentrated in Uttar Pradesh, Gujarat, and Rajasthan. After a few decades of stagnancy, India's Urea production capacity has increased over the past five years with the commissioning of six new plants. At present, the country's total Urea manufacturing capacity stands at 31.3 million metric tonnes (MMT).

Table 4.2: Key Characteristics of Urea Plants in India

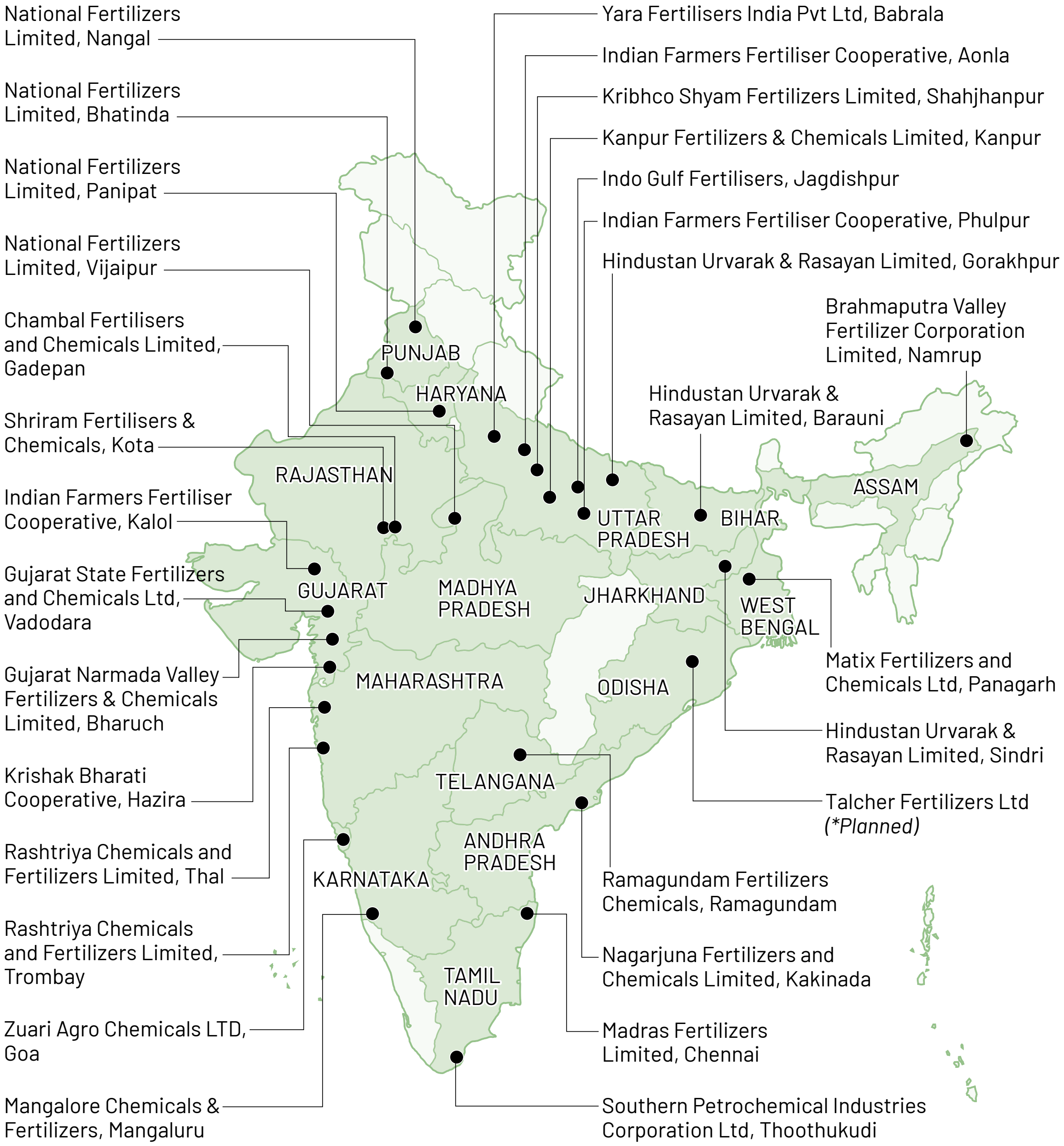
S. No.	Plant name	Acronym	Location	Age as in 2024	Reas-sessed capacity (MMT) 2022-23	Average Energy Efficiency (2017-22) Gcal/MT Urea
1	National Fertilizers Limited, Nangal-II	NFL, Nangal-II	Nangal, Punjab	46	0.479	6.7
2	National Fertilizers Limited, Bhatinda	NFL, Bhatinda	Bhatinda, Punjab	45	0.512	7
3	National Fertilizers Limited, Panipat	NFL, Panipat	Panipat, Haryana	45	0.512	6.9
4	National Fertilizers Limited, Vijaipur	NFL, Vijaipur	Vijaipur, Madhya Pradesh	36	0.999	5.8
5	National Fertilizers Limited, Vijaipur Expn.	NFL, Vijaipur Expn.	Vijaipur, Madhya Pradesh	27	1.066	5.5
6	Brahmaputra Valley Fertilizer Corporation Limited, Namrup-II	BVFCL, Namrup-II	Namrup, Assam	55	0.24	20.5
7	Brahmaputra Valley Fertilizer Corporation Limited, Namrup-III	BVFCL, Namrup-III	Namrup, Assam	55	0.27	14.3
8	Rashtriya Chemicals and Fertilizers Limited, Trombay-V	RCF, Trombay-V	Trombay, Maharashtra	51	0.33	6.9
9	Rashtriya Chemicals and Fertilizers Limited, Thal	RCF, Thal	Thal, Maharashtra	39	2	5.8
10	Madras Fertilizers Limited, Chennai	MFL, Chennai	Chennai, Tamil Nadu	53	0.487	7.7
11	Indian Farmers Fertiliser Cooperative, Kalol	IFFCO, Kalol	Kalol, Gujarat	50	0.545	5.6
12	Indian Farmers Fertiliser Cooperative, Phulpur	IFFCO, Phulpur	Phulpur, Uttar Pradesh	44	0.697	5.9
13	Indian Farmers Fertiliser Cooperative, Phulpur Expn.	IFFCO, Phulpur Expn.	Phulpur, Uttar Pradesh	27	0.999	5.3
14	Indian Farmers Fertiliser Cooperative, Aonla	IFFCO, Aonla	Aonla, Uttar Pradesh	36	0.999	5.2
15	Indian Farmers Fertiliser Cooperative, Aonla Expn.	IFFCO, Aonla Expn.	Aonla, Uttar Pradesh	28	0.999	5.1
16	Krishak Bharati Cooperative, Hazira	KRIBHCO, Hazira	Hazira, Gujarat	38	2.194	5.5
17	Gujarat State Fertilizers and Chemicals Ltd, Vadodara I & II	GSFC, Vadodara I & II	Vadodara, Gujarat	57	0.371	6

Table 4.2 continued

S. No.	Plant name	Acronym	Location	Age as in 2024	Reas-sessed capacity (MMT) 2022-23	Average Energy Efficiency (2017-22) Gcal/MT Urea
18	Shriram Fertilisers & Chemicals, Kota	SFC, Kota	Kota, Rajasthan	55	0.38	6.7
19	Kanpur Fertilizers & Chemicals Limited, Kanpur	KFCL (DIL), Kanpur	Kanpur, Uttar Pradesh	54	0.723	7
20	Zuari Agro Chemicals LTD, Goa	ZACL, Goa	Zuarinagar, Goa	50	0.399	6.8
21	Southern Petrochemical Industries Corporation Ltd, Thoothukudi	SPIC, Tuticorin	Thoothukudi, TamilNadu	45	0.759	6.7
22	Mangalore Chemicals & Fertilizers, Mangaluru	MCF, Mangalore	Mangaluru, Karnataka	48	0.425	6.4
23	Gujarat Narmada Valley Fertilizers & Chemicals Limited, Bharuch	GNFC, Bharuch	Bharuch, Gujarat	42	0.637	6.3
24	Indo Gulf Fertilisers, Jagdishpur	IGF, Jagdishpur	Jagdishpur, Uttar Pradesh	36	1.102	5.4
25	Nagarjuna Fertilizers and Chemicals Limited, Kakinada-I	NFCL, Kakinada-I	Kakinada, Andhra Pradesh	32	0.767	5.7
26	Nagarjuna Fertilizers and Chemicals Limited, Kakinada-II	NFCL, Kakinada-II	Kakinada, Andhra Pradesh	26	0.752	5.7
27	Chambal Fertilisers and Chemicals Limited, Gadepan-I	CFCL, Gadepan-I	Gadepan, Rajasthan	30	1.023	5.5
28	Chambal Fertilisers and Chemicals Limited, Gadepan-II	CFCL, Gadepan-II	Gadepan, Rajasthan	25	0.99	5.4
29	Chambal Fertilisers and Chemicals Limited , Gadepan-III	CFCL, Gadepan-III	Gadepan, Rajasthan	5	1.271	5.1
30	Yara Fertilisers India Pvt Ltd, Babrala	Yara, Babrala	Babrala, Uttarpradesh	30	1.155	5.2
31	Kribhco Shyam Fertilizers Limited, Shahjhanpur	KSFL, Shahjhanpur	Shahjhanpur, Uttar Pradesh	29	0.865	5.5
32	Matix Fertilizers and Chemicals Ltd, Panagarh	Matix Fertilizers and Chemicals Ltd.	Panagarh, West Bengal	3	1.27	5.3
33	Hindustan Urvarak & Rasayan Limited , Barauni	HURL Barauni	Barauni, Bihar	2	1.27	5.3
34	Hindustan Urvarak & Rasayan Limited , Sindri	HURL Sindri	Sindri, Jharkhand	2	1.27	5.3
35	Hindustan Urvarak & Rasayan Limited , Gorakhpur	HURL Gorakhpur	Gorakhpur, Uttar Pradesh	3	1.27	5.3
36	Ramagundam Fertilizers Chemicals , Ramagundam	RFCL Ramagundam	Ramagundam, Telangana	3	1.27	5.3
Total					**31.293**	

Source: Department of Fertiliser and Fertiliser Association of India
Note: Since we do not yet have data for the considered period from the five youngest plants, their efficiency has been assumed to be the same as that in HURL Sindri.

Map 4.1: Urea Manufacturing Plants in India



Source: iFOREST Analysis

Urea plants in India are relatively old– the majority of existing manufacturing facilities were established between 1970 and 2000. Some date back even further. The average capacity-weighted age of all the plants is 29 years.

Approximately 45% of these units are over 40 years old. These older plants are characterised by smaller production capacities and lower energy efficiencies. Another 40% of the plants, aged between 20 and 40 years, exhibit improved energy efficiency and larger production capacities. The remaining 15%, which accounts for six facilities, have been installed in only the last five years. As such, they have the largest rated capacities and incorporate cutting-edge technology. Given the significant variation in the age and performance of these plants, a transition strategy needs to be tailored to fit each of their unique needs.

Table 4.3: Averaged Capacity and Efficiency of India's Urea Plants Across Age Groups

Age Band	Number of plants	Combined Capacity of Plants (MMT/Annum)	Average Capacity (MMT/Annum)	Average Energy Efficiency (Gcal/ MT)
50 years and above	9	3.74	0.42	6.7
40-49 years	7	4.01	0.57	6.6
30-39 years	8	10.24	1.28	5.5
20-29 years	6	5.67	0.95	5.4
10-19 years	-	-	-	-
< 10 years	6	7.62	1.27	5.1

Source: iFOREST Analysis

4.2 Technology Transition Strategy

To decarbonise the manufacturing of Urea in India, the existing Grey Urea plants need to be converted to either Blue or Green Urea plants. The conversion to Blue or Green Urea can occur either as Greenfield deployments or Brownfield deployments. Depending on their age, performance and, ultimately, the cost of production, existing plants will decide on their transition strategy, as detailed below.

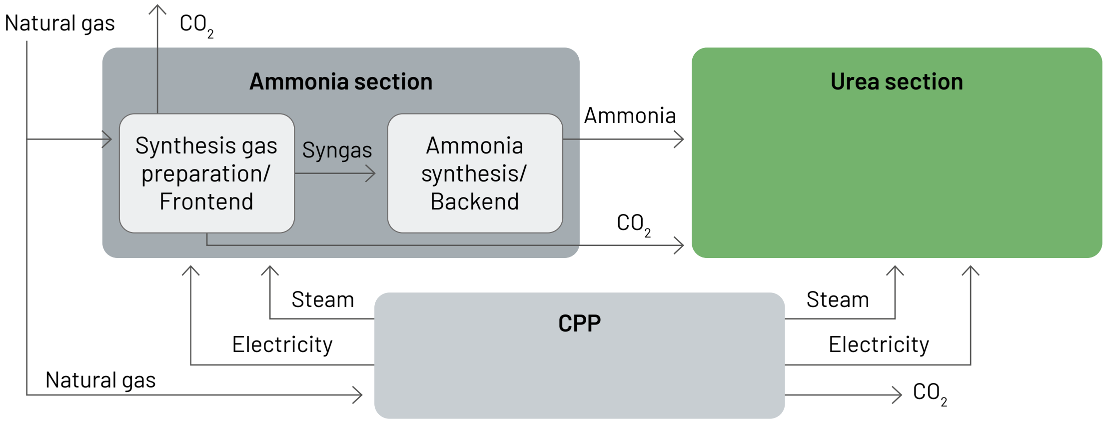
(a). Greenfield Grey Urea

A Greenfield Grey Urea plant is primarily divided into two major sections– the Ammonia section and the Urea section. The Ammonia section is further divided into a front-end section where synthesis gas is prepared and a back-end where Ammonia is synthesised.

- Synthesis gas preparation (Front-end): Encompasses the entire process of using NG to prepare Synthesis gas. Synthesis gas is a mixture of hydrogen (from natural gas) and nitrogen (from atmospheric air) in a desired ratio of 3:1. This process also produces CO_2, which is captured and sent to the Urea section. Processes such as desulphurisation, steam reforming, shift conversion, CO_2 absorption and methanation all occur in this section.
- Ammonia synthesis (Back-end): Includes synthesis gas compressors, Ammonia synthesisers, and Ammonia storage. The gaseous mixture of H_2 and N_2 that comprise Synthesis gas (or Syngas), react with each other following the Haber-Bosch process to produce Ammonia.
- Urea synthesis: In the Urea section, Ammonia and CO_2 from the Ammonia section are synthesised to produce Urea.

The existing Grey Urea plants need to be converted to either Blue or Green Urea plants. The conversion to Blue or Green Urea can occur either as Greenfield deployments or Brownfield deployments.

Figure 4.2: Greenfield Grey Urea Plant



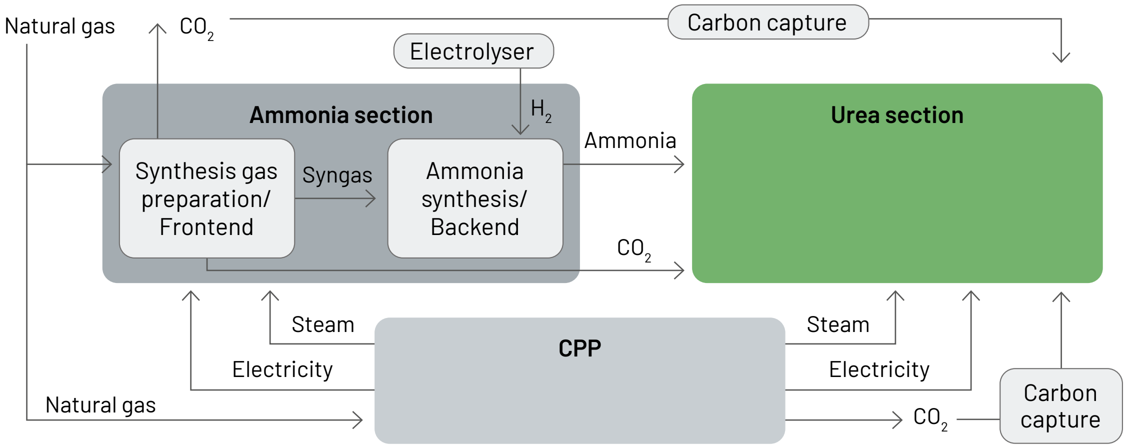
Source: iFOREST analysis

(b). Greenfield Blue Urea

Blue Urea facilities aim to capture and utilise all CO_2 emissions, including both those generated directly by its processes (from the reformers) and those released from the CPPs that supply electrical energy. By doing so, these plants can expect significant reductions in overall CO_2 emissions. However, this results in a surplus of CO_2 available for Urea synthesis. To address this excess of CO_2, the amount of NG being used as feedstock is correspondingly reduced. This in turn causes a relative shortfall of H_2 from SMR. As a solution to meeting this deficit in H_2, the plant blends Green H_2 using electrolysers, powered by renewable energy, with the H_2 obtained from SMR to ensure unchanged capacity for both Ammonia and Urea production.

Consequently, NG consumption in Blue Urea production is lower than required by Grey Urea production for plants of comparable size. The N_2 source for Blue Urea remains unchanged from that used in Grey Urea. The processes for synthesising Ammonia and Urea in a Blue Urea facility are the same as in Grey Urea facilities–the back end of the Ammonia plant and the entire Urea plant are unchanged. However, the front end of the Ammonia Synthesis section is adjusted in capacity to accommodate for the reduced flow of NG. Additionally, an electrolyser is integrated into the Ammonia plant, and a Carbon capture unit is added to both the CPP and Ammonia front end section.

Figure 4.3: Greenfield Blue Urea Plant

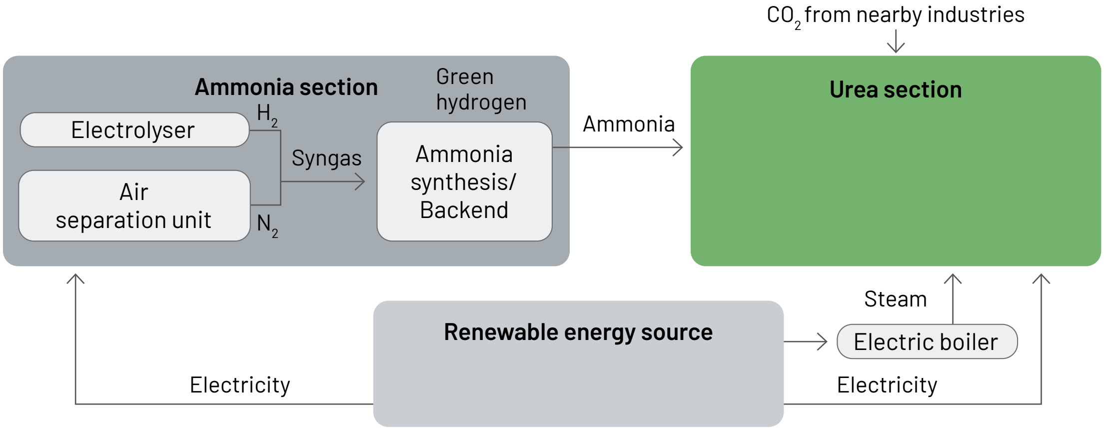


Source: iFOREST analysis

(c). Greenfield Green Urea plant

In a Green Urea facility, H_2 is sourced exclusively from an electrolyser, eliminating the need for NG. N_2 is produced through an ASU, while CO_2 is sourced externally from nearby carbon-emitting facilities. In this setup, the electrolyser and ASU replace Grey Urea plants' synthesis gas preparation section. The back-end Ammonia and Urea synthesis sections in the Green Urea plant are identical to those found in Grey Urea production processes.

Figure 4.4: Greenfield Green Urea Plant

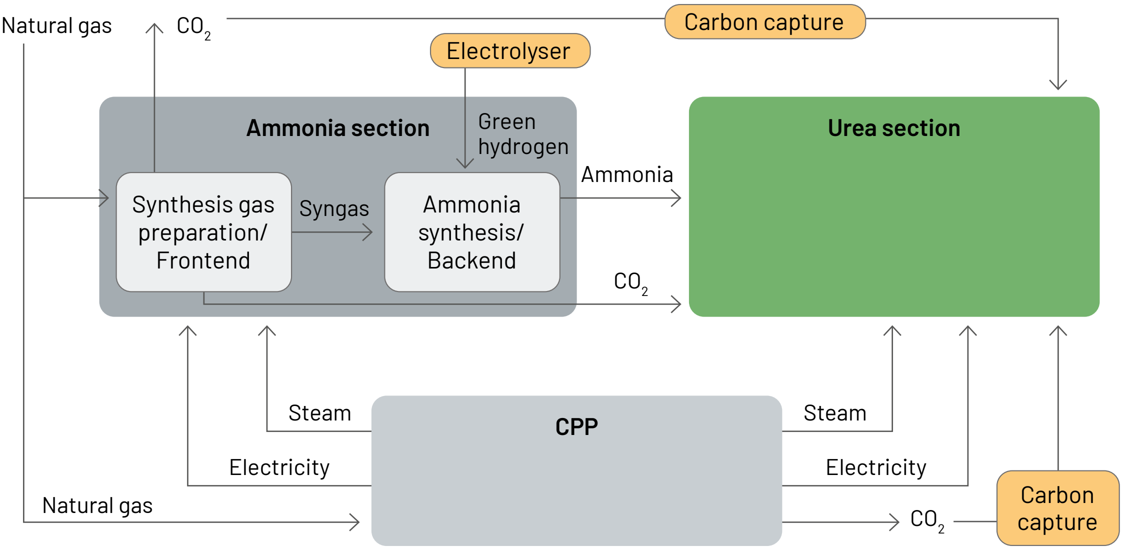


Source: iFOREST analysis

(d). Brownfield Blue Urea plant

All the existing equipment and infrastructure of a Grey Urea plant is utilised in a Brownfield Blue Urea facility. However, the plant is upgraded by the installation of a new electrolyser to generate supplemental H_2 and carbon capture systems to sequester CO_2 emissions from the primary reformer and the captive power plant.

Figure 4.5: Brownfield Blue Urea plant

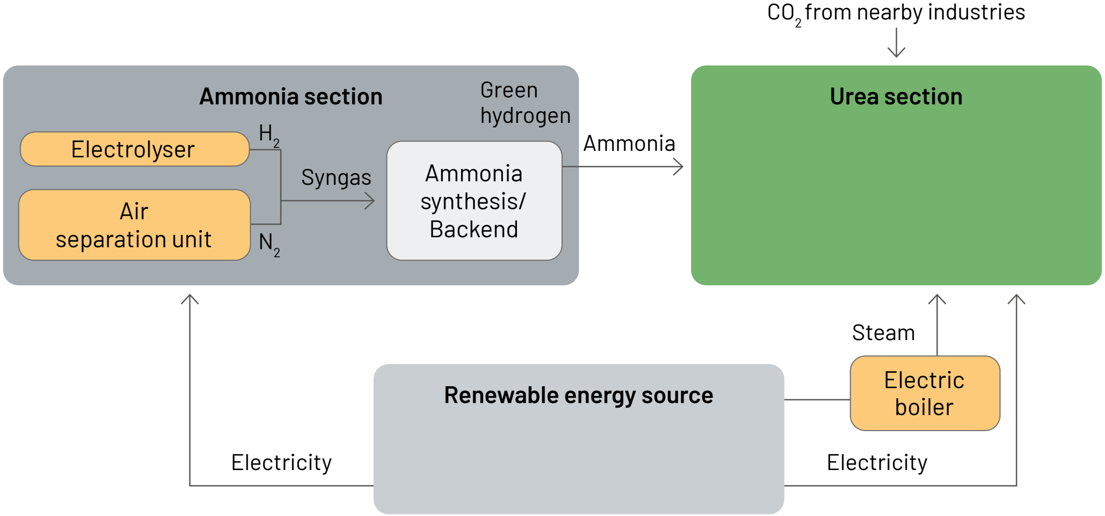


Source: iFOREST analysis

(e). Brownfield Green Urea

In the conversion to a Brownfield Green Urea plant, the entire synthesis gas section, or the Ammonia front-end, of a Grey Urea plant is substituted with an electrolyser and an ASU. The captive power plant is supplanted by renewable energy sources, and an electric boiler is installed to provide the necessary steam. This new equipment is integrated to work in conjunction with the existing Ammonia synthesiser or Ammonia back-end and the Urea synthesiser section.

Figure 4.6: Brownfield Green Urea plant



Source: iFOREST analysis

4.3 Modelling technology transition

The voluntary decarbonisation of the fertiliser industry will be primarily driven by economic factors. To evaluate the decarbonisation pathways for the fertiliser industry in India, an economic modelling approach was employed using the Levelised Cost of Urea (LCOU). Given that the LCOU is influenced by various factors such as future costs of key technologies like electrolysers, as well as commodities like NG and renewable electricity, multiple scenarios were developed to assess the impact of these variables on decarbonisation pathways.

To evaluate the decarbonisation pathways for the fertiliser industry in India, an economic modelling approach was employed using the Levelised Cost of Urea.

The modelling was conducted in two phases. Phase 1 involved sector-wide modelling, where decisions regarding the decommissioning of existing plants or their replacement with Greenfield or Brownfield plants—utilizing Grey, Blue, or Green Urea—were made based on a country-level cost analysis. This provided a broad overview of the potential decarbonisation pathways for the sector.

In Phase 2, plant-specific modelling was conducted for all 36 Urea plants, using detailed plant-specific data to evaluate the feasibility of various decarbonisation strategies for each plant. This phase offered tailored decarbonisation pathways for each plant, thereby contributing to a detailed roadmap for the entire sector.

The details of medelling including technical specifications, modelling framework and cost assumptions are as provided in Annexure 4.

4.3.1 Sectoral analysis

The primary objective of this analysis is to gain a comprehensive understanding of the economic feasibility of decarbonisation of the Urea sector from a central planner's perspective. This involves making decisions on whether to retrofit or decommission existing plants, or replace them with Greenfield plants, based on a country-level cost analysis. For this, a techno-economic analysis of 34 Urea plants[6] in India was conducted for an optimisation period from 2025 to 2050. Using LCOU as the key parameter, the aim was to identify the most cost-effective production pathway while meeting India's future Urea demand. Additionally, various scenarios were used to assess the impact of changes in future costs of technologies and commodities critical for decarbonisation.

The modelling was conducted using an optimisation model with a cost-minimisation objective function. For given techno-economic parameters, the model estimates the most cost-optimal way to meet the country's urea demand. This could involve shutting down the most energy-inefficient plants and/or retrofitting certain plants to Blue or Green Urea production techniques if the model deems it cheaper than continuing with Grey Urea production. For any new installations (Greenfield plants), either to meet additional urea demand or to replace an inefficient existing plant, it can be based on Grey, Blue, or Green Urea techniques. The techno-economic parameters for these Greenfield plants are based on Hindustan Urvarak & Rasayan Limited (HURL), Sindri, the newest plant for which operational data is available.

The urea demand projection is based on the "iFOREST Optimal" scenario, as discussed in Section 3.3. Regarding import and export assumptions, no urea import is considered for the entire optimisation horizon, aligning with India's goal of achieving self-sufficiency in urea by 2025. Based on historical trade data, a urea export of up to 5% of the annual demand is allowed in the model. Regardless of the year, a constant export revenue of $450/MT Urea is assumed. It should be noted that inflation is not considered in this analysis.

The sectoral modelling was done to assess the economic feasibility of decarbonisation of the Urea sector from a central planner's perspective.

To assess the impact of uncertainty in future cost developments for crucial technologies and commodities, three scenarios were modelled:

(i) **Median scenario:** This scenario assumes a "middle way" for future cost developments. For electrolysers, the average value of the cost range provided by the IEA is assumed. For NG cost projections, the reference case of US Henry Hub NG price projections is used. Green electricity costs are assumed to match the Round The Clock (RTC) renewable energy supply contracts signed in India in recent years over the entire optimisation horizon.

(ii) **Optimistic scenario:** This scenario assumes conditions favourable to decarbonisation. For electrolysers, the lower limit of the cost range provided by the IEA is used. Higher NG costs are advantageous for decarbonisation; hence, the "Low Economic Growth" scenario of Henry Hub projections, which forecasts higher future NG prices, is used. Green electricity costs are considered to be 20% lower than those in the median scenario.

(iii) **Pessimistic scenario:** This scenario assumes conditions unfavourable to decarbonisation. For electrolysers, the upper limit of the cost range is used. Lower NG costs reinforce current NG-based Grey Urea production techniques, thus discouraging decarbonisation. Therefore, the "High Oil and Gas Supply" scenario of Henry Hub projections, which forecasts lower future NG prices, is used. Green electricity costs are considered to be 20% higher than those in the median scenario.

4.3.2 Plant-level analysis

The main objective of this analysis is to investigate the economic feasibility of different decarbonisation strategies, tailored for each existing Urea plant, by performing a plant-level LCOU analysis. This analysis assumes the same economic assumptions as the "median" scenario in the sectoral analysis describes above. However, in comparison to the sectoral analysis, this analysis also considers inflation in its cost analysis.

A Urea plant can achieve decarbonisation using several possible ways (called as *Decarbonisation Scenarios* hereafter), such as, by continuing its Grey Urea operation until retirement and then getting replaced by a Greenfield Green Urea plant, or by first getting retrofitted to a Brownfield Green Urea plant and then getting replaced by a Greenfield Green Urea plant upon retirement. Furthermore, since the Urea plants in India widely differ in their age (2 years to as high as 57 years), these decarbonisation strategies should be tailored based on a plant's retirement age. Thus, to be able to recommend plant-specific decarbonisation strategies, the following techno-economic modelling were undertaken:

(a). Greenfield plants

Future Urea plants can adopt Grey, Blue, or Green Urea production routes, each with varying costs due to technological differences. Additionally, the commissioning year will affect these costs because of factors like annual variations in NG prices and anticipated reductions in electrolyser costs due to technological advancements. Therefore, for Greenfield plants we estimate the LCOU for each production route for commissioning years between 2025 and 2050, with a project lifetime limited to 25 years. Given that 1.27 MMT/annum capacity is prevalent among recent Urea plant installations in India, with HURL Sindri being one of the most recently commissioned, this plant is considered as a benchmark for future Greenfield installations. Consequently, the operating parameters for modelling Greenfield plants are based on those of HURL Sindri[7].

The plant-level modelling was done to investigate economic feasibility of decarbonising each operational plant based on their specification and performance.

This cost model serves not only as a reference for future, standalone Greenfield installations, but it is also used in the different scenarios for existing plants, wherever the option of retrofitting it with a Greenfield plant is considered.

(b). Existing plants

India has a total of 36 Urea plants, with commissioning dates ranging from 1969 to 2022. This results in a wide range of retirement years (assuming a useful plant life of 60 years), necessitating individualized decarbonisation scenarios. To address this, existing Urea plants are grouped based on their age, and tailored decarbonisation strategies are developed for each group. The plants are categorized into five groups: "PG1" to "PG5". PG1 represents the oldest plants, set to retire between 2025 and 2030, while PG5 represents the youngest plants, expected to retire after 2075.

These plant groups and their respective decarbonisation scenarios are outlined below. Any scenario that involves the continued operation of an existing plant as a Grey Urea plant will require periodic renovation and modernization (R&M) to ensure efficient and uninterrupted operation. It is assumed that the plant's average operation and maintenance (O&M) costs, which also includes new capital expenditure, observed over the past five years, adjusted for inflation, will be sufficient for its continued operation through R&M.

Plants retiring between 2025-2030 (PG1): This group consists of the oldest of all Urea plants in the country. The four decarbonisation strategies considered for this group are:

i. Greenfield Grey after retirement
ii. Greenfield Blue after retirement
iii. Greenfield Green after retirement
iv. Continue plant operation until 2050 with R&M

Plants retiring between 2030-2040 (PG2): The Urea plants in this group have up to 16 years of remaining plant operation (as of in 2024), allowing the consideration of intermediate decarbonisation strategies until their retirement. Their decarbonisation strategies are:

i. Greenfield Blue after retirement
ii. Greenfield Green after retirement
iii. Brownfield Blue in 2025 and then to a Greenfield Blue plant between 2030-2040
iv. Brownfield Green in 2025 and then to a Greenfield Green plant between 2030-2040
v. Continue plant operation until 2050 with R&M

Plants retiring between 2040-2050 (PG3): The Urea plants in this group have up to 26 years of remaining plant operation (as of 2024). The decarbonisation scenarios modelled for them are:

i. Greenfield Blue after retirement
ii. Greenfield Green after retirement
iii. Brownfield Blue between 2025-2050 until retirement and then to a Greenfield Green plant
iv. Brownfield Green between 2025-2050 until retirement and then to a Greenfield Green plant
v. Continue plant operation until 2050 with R&M

Plants retiring between 2050-2060 (PG4): These Urea plants in this group have up to 36 years of remaining plant operation (as of in 2024). Their decarbonisation scenarios are:

i. Greenfield Blue after retirement
ii. Greenfield Green after retirement
iii. Brownfield Blue between 2025-2050
iv. Brownfield Green between 2025-2050
v. Continue plant operation until 2050

Plants retiring after 2075 (PG5): This group consists of the newest Urea plants with at least 51 years of remaining plant operation (as of in 2024). Their decarbonisation strategies are:

i. Greenfield Blue after 25 years of plant operation
ii. Greenfield Green after 25 years of plant operation
iii. Brownfield Blue after 25 years of plant operation
iv. Brownfield Green after 25 years of plant operation
v. Continue plant operation until 2050

The methodology and assumptions are detailed in Annexure 4.

The existing plants are categorized into five groups: PG1 to PG5 for modelling. PG1 includes the oldest plants retiring between 2025 and 2030, while PG5 includes the youngest plants retiring after 2075. Multiple scenarios were then run for each group to arrive at the most cost-effective decarbonisation pathways.

THE LIFE OF A GREY UREA PLANT

In India, the expected lifespan of a Urea plant is considered to be 25 years, within which it is allowed to depreciate by 90%, with all equity and debt being recovered. Yet, the actual operational life of these plants often extends well beyond 25 years. Numerous Urea manufacturing facilities in India have been functioning for over 50 years, thanks to ongoing R&M efforts. Following discussions with industry stakeholders and experts, the operational lifespan of a Urea plant has been assumed as 60 years for the modelling exercise.

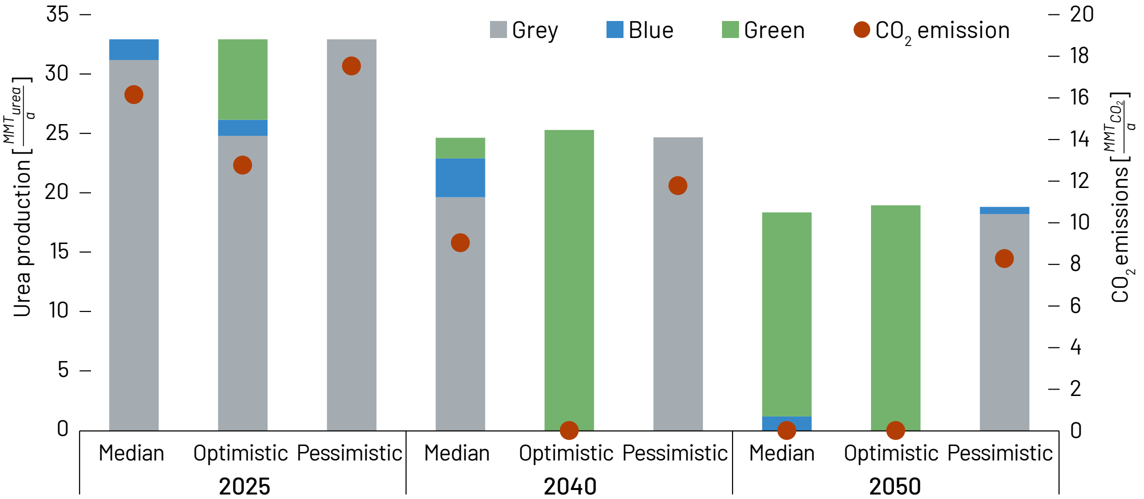
4.4 Results

The results are divided into two main sections: sectoral and plant-level analysis. The sectoral analysis results briefly discuss the possible sectoral decarbonisation that is economically feasible under different scenarios. The plant-level results elaborate the findings for plants under each plant group (PG).

4.4.1 Sectoral Result

Graph 4.1 illustrates India's projected annual Urea production (by type) and CO_2 emissions for selected years under various scenarios. The Urea production values, shown in million tons per annum $[\frac{MMT_{urea}}{a}]$, are calculated from the model results by summing them across all current and future Urea plants in India for each year, differentiating them only based on the chosen production technique (Grey, Blue or Green) in individual plants. The depicted annual CO_2 emissions $[\frac{MMT_{CO_2}}{a}]$ are summed across the production techniques. The illustration is limited to selected years (2025, 2040 and 2050) to maintain readability.

Graph 4.1: Level of achievable decarbonisation in India's annual Urea production and CO_2 emissions under different scenarios



Source: iFOREST analysis

Looking at the annual urea production, it can be observed that it decreases rapidly from approximately 32.9 $\frac{MMT_{urea}}{a}$ in 2025 to approximately 18.7 $\frac{MMT_{urea}}{a}$ in 2050 due to the projected reduction in urea demand in India. The production volumes across scenarios vary slightly for any given year, as the model attempts to find the most cost-optimal combination of plants that are allowed to operate (along with their urea type) based on the defined cost assumptions for each scenario. This results in slightly deviating annual urea production across these scenarios.

In 2025, the median and optimistic scenarios indicate the start of decarbonisation, with the latter scenario showing a stronger tendency (21% green and 4% blue). This also results in it having a much lower CO_2 emission as compared to the median scenario (12.7 vs 16.1 $\frac{MMT_{CO_2}}{a}$). The pessimistic scenario, on the other hand, indicate a 100% grey urea production along with a slightly higher CO_2 emission (17.5 $\frac{MMT_{CO_2}}{a}$).

By 2040, the optimistic scenario shows a dramatic shift toward decarbonisation of the sector with 100% urea being produced using the green production technique, and thus resulting in no CO_2 emissions. The median scenario shows a relatively less decarbonisation, with only 13% and 7% of the urea produced using the blue and green production techniques respectively, resulting in a CO_2 emission of approximately 9 $\frac{MMT_{CO_2}}{a}$. The pessimistic scenario shows a continuation of 100% grey urea production, leading to a CO_2 emission of 11.7 $\frac{MMT_{CO_2}}{a}$.

Although it started with a slower decarbonisation, the median scenario is almost completely decarbonised by 2050, with 93% and 7% of its urea being produced using the green and blue production techniques respectively. The pessimistic scenario does not indicate any significant decarbonisation of its production technique, producing only 3% of the urea using the blue production technique.

Overall, an almost 100% decarbonisation is economically achievable in two of the three scenarios by 2050. The median scenario, even with its "middle path" for future cost assumptions can comfortably achieve 93% green urea production by 2050. In the pessimistic scenario, the share of grey urea, and thus the resulting CO_2 emissions, remain relatively high.

The sectoral analysis shows that an almost 100% decarbonisation is economically feasible in two of the three scenarios by 2050. Even the median scenario achieves 93% green urea production by 2050.

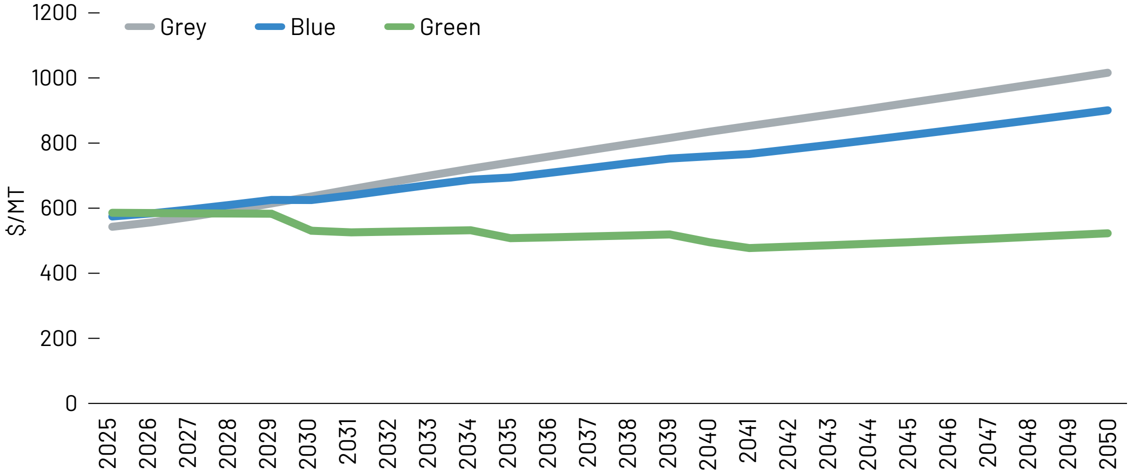
4.4.2 Plant-level Results

4.4.2.1 Greenfield plant

The estimated levelised cost from a model Greenfield plant for Grey, Blue and Green Urea is shown in Graph 4.2. These LCOUs account for capital repayment and O&M costs over 25 years for plants set up in each year between 2025 and 2050.

The modelling results indicate that the LCOU of Greenfield Grey Urea is likely to remain the cheapest until 2028. However, post-2028, the cheapest Urea from a Greenfield plant in India is likely to be Green Urea. The LCOU in a Green Urea plant in 2030 is about 20% lower than that in a Grey Urea plant. This difference increases to almost 100% by 2050. On the other hand, a Greenfield Blue Urea plant is not viable in most years. Post-2026, it is more expensive than Green Urea and only marginally cheaper than Grey Urea.

Graph 4.2: LCOU of a Model Greenfield Grey, Blue and Green Urea Plant



Source: iFOREST analysis

Table 4.4: LCOU of Greenfield Grey, Blue and Green Urea plants

Installation Year	LCOU ($/ MTUrea)		
	Grey	Blue	Green
2025	541	572	588
2030	635	623	531
2035	740	694	507
2040	835	760	494
2045	924	825	494
2050	1018	903	523

Source: iFOREST analysis

This analysis indicates that there is no economic rationale to install Greenfield Grey or Blue Urea plant in India post 2028.

4.4.2.2 Plants retiring between 2025-2030 (PG1)

The following plants fall under this category:

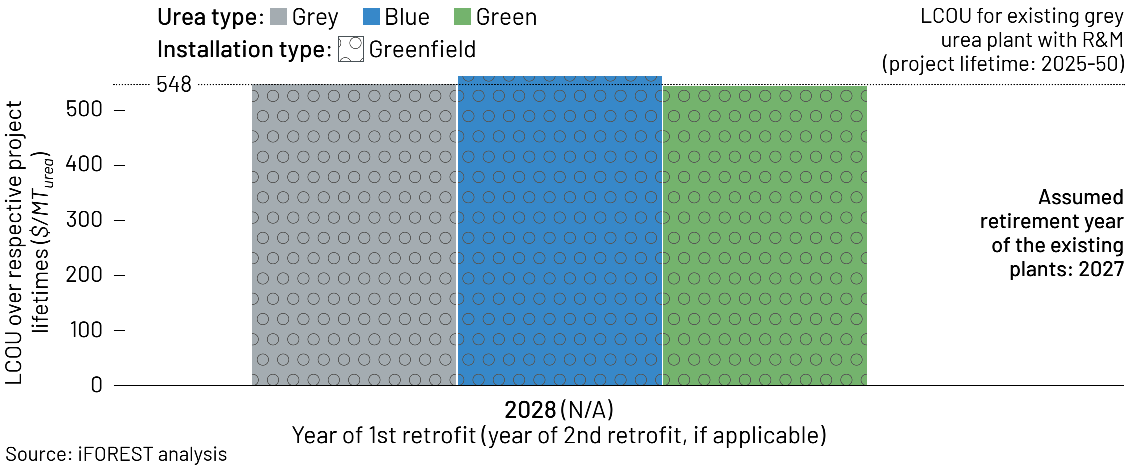
1. GSFC Vadodara
2. BVFCL Namrup II
3. BVFCL Namrup III
4. SFC Kota
5. KFCL Kanpur

The results indicate that the most cost-effective pathway is to transition to Greenfield Green Urea post-retirement. However, for some of the plants, the cost of Greenfield Grey Urea plant is only marginally higher than Greenfield Green Urea. This is illustrated below using the case of GSFC Vadodara and SFC Kota.

GSFC Vadodara

GSFC Vadodara is the oldest operating Urea plant in India. It was installed in the year 1967, and its reassessed capacity is 0.37 MMT per annum (2022-23). Graph 4.3 illustrates the estimated LCOU for its decarbonisation strategies. As observed, replacing this plant with a Greenfield Green Urea plant after retirement is the most economical, and thus our recommended, strategy ($544 /MTUrea). However, the other two strategies — continued operation as Brownfield Grey Urea with R&M until 2050 (LCOU: $548/MTUrea) and replacement with Greenfield Grey Urea plant (LCOU: $548 /MTUrea) provide comparable costs and can also be taken into consideration.

Graph 4.3: LCOUs under different decarbonisation strategies for GSFC Vadodara

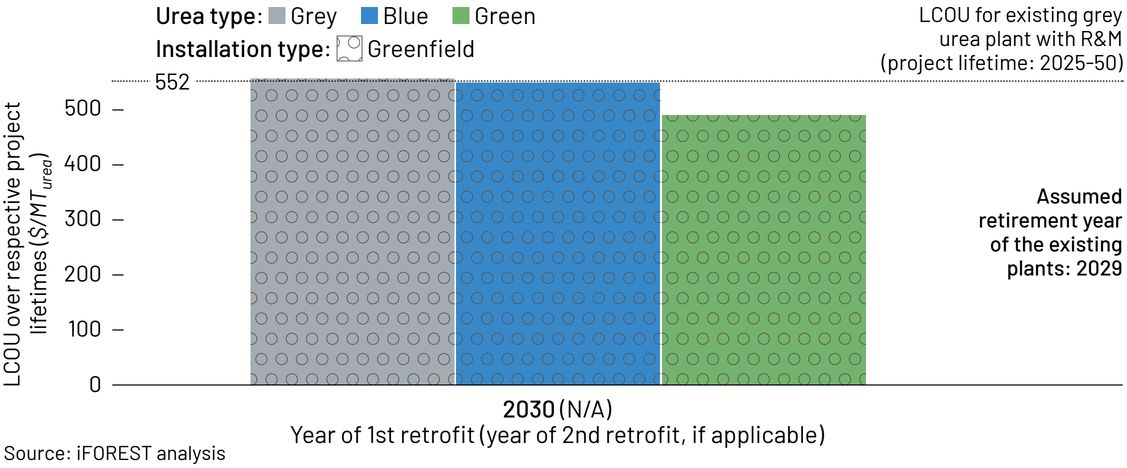


Source: iFOREST analysis

SFC Kota

This is another of the older plants in India. It was installed in 1969 and was shifted from naphtha to NG in 2007. Graph 4.4 shows the LCOU under different scenarios. The plant is recommended to operate on Natural Gas till its retirement after which it should convert to Greenfield Green Urea. This strategy gives the LCOU of $489/ MTUrea. The LCOU of Greenfield Green Urea at SFC Kota is around 12% less than Grey and 10.7% lower than Blue Urea.

Graph 4.4: LCOU under different scenarios at SFC Kota



Source: iFOREST analysis

4.4.2.3 Plants retiring between 2030-2040 (PG2)

The following plants fall in this category:

1. MFL Chennai
2. RCF Trombay
3. IFFCO Kalol
4. ZACL Goa
5. MCF Manglore
6. NFL Nangal
7. NFL Bhatinda
8. NFL Panipat
9. SPIC Tuticorin
10. IFFCO Phulpur

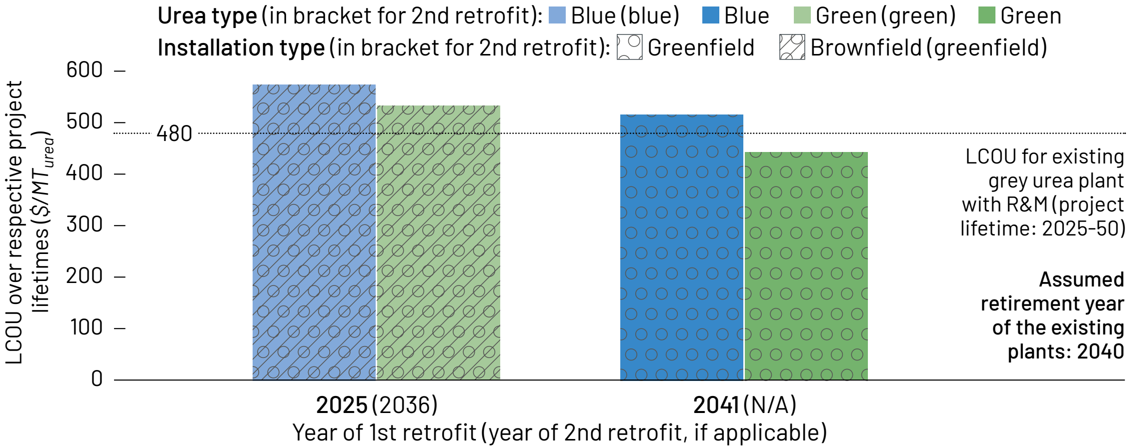
The Urea plants in this group have up to 16 years of remaining plant operation (as of in 2024), allowing the consideration of intermediate decarbonisation strategies until their retirement. However, the results indicate that for this category as well, the most

cost-effective pathway is to transition to Greenfield Green Urea post-retirement. This is illustrated below using the case of IFFCO Phulpur and SPIC Tuticorin.

IFFCO Phulpur

The plant was commissioned in the year 1981 and was renovated in 2008. Its feedstock was changed from Naphtha to NG in 2006. Reassessed capacity in 2022-23 is 0.697 MMT per annum. Analysis of different scenarios shows that converting the plant to Greenfield Green Urea after its retirement give the lowest LCOU of $442 / MTUrea (see Graph 4.5).

Graph 4.5: LCOU under different scenarios at IFFCO Phulpur

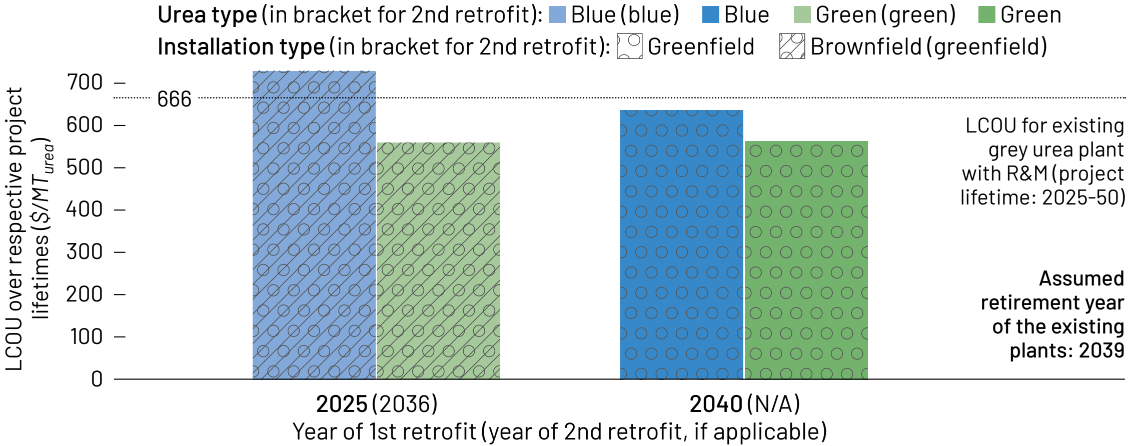


Source: iFOREST analysis

SPIC Tuticorin

SPIC Tuticorin was commissioned in 1979 and transitioned from naphtha to natural gas in 2021. The reassessed capacity for 2022-23 is 0.759 MMT per annum. The lowest Levelised Cost of Urea (LCOU) is achieved if the plant switches to Brownfield Green Urea production in 2025, followed by a transition to Greenfield Green Urea production between 2030 and 2040, with an LCOU of $559/ MTUrea. However, changing to Greenfield Green Urea production in 2040 also results in a slightly higher LCOU of $563/ MTUrea. Therefore, it is recommended that the plant transitions to Greenfield Green Urea production in 2040 to avoid dual transition.

Graph 4.6: LCOU under different scenarios at SPIC Tuticorin



Source: iFOREST analysis

It is financially viable for most plants to operate using NG till retirement and then be shifted directly into Greenfield Green Urea, as is seen with the IFFCO Phulpur. Only one plant, namely, SPIC Tuticorin, will find it marginally cost-effective to switch to Brownfield Green Urea in the year 2025 and then to Greenfield Green Urea in any year between 2030 and 2040. Of the 10 plants in this category, the following 9 should operate using NG till retirement and then convert to Greenfield Green Urea:

1. NFL Nangal
2. NFL Bhatinda
3. NFL Panipat
4. RCF Trombay
5. MFL Chennai
6. IFFCO Kalol
7. IFFCO Phulpur
8. ZACL Goa
9. MCF Mangalore

SPIC Tuticorin too should shift to Greenfield Green Urea as the savings from first shifting to Brownfield and then to Greenfield Green Urea, as opposed to directly shifting to Greenfield Green Urea, is less than 1%.

It would be optimal to shift plants retiring between 2030-40 directly to Greenfield Green Urea at retirement.

Thus, it can be concluded that for this category of plants, it would be optimal to shift directly to Greenfield Green Urea at retirement.

4.4.2.4 Plants retiring between 2040-50 (PG3)

This category contains six plants:

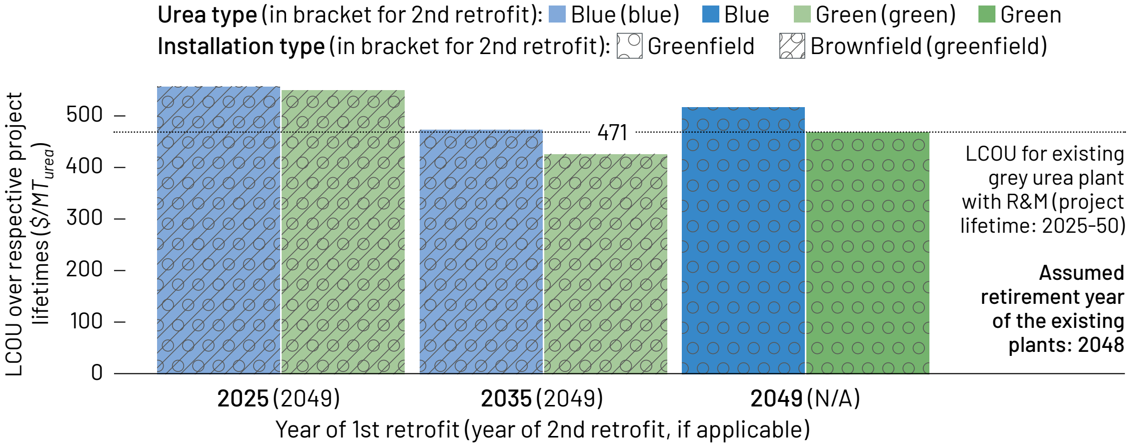
1. GNFC Bharuch
2. RCF Thal
3. KRIBHCO Hazira
4. NFL Vijaypur
5. IFFCO Aonla
6. IGF Jagdishpur

The Urea plants in this group have up to 26 years of remaining plant operation (as of in 2024). The modelling results suggest that the most cost-effective route is to transition these plants to Brownfield Green Urea in the year 2035 and then convert to Greenfield Green Urea on retirement. This is illustrated below using the examples of IGF Jagdishpur and KRIBHCO Hazira:

IGF Jagdishpur

The plant was commissioned in 1988, with a reassessed capacity of 1.102 MMT per annum for 2022-23. It is recommended to operate on natural gas until 2035, then transform into a brownfield Green Urea plant, and finally transition to a Greenfield Green Urea plant upon retirement in 2048. This scenario results in the lowest LCOU at $427/ MTUrea. The graph below illustrates the LCOU under various scenarios.

Graph 4.7: LCOU under different scenarios at IGF Jagdishpur



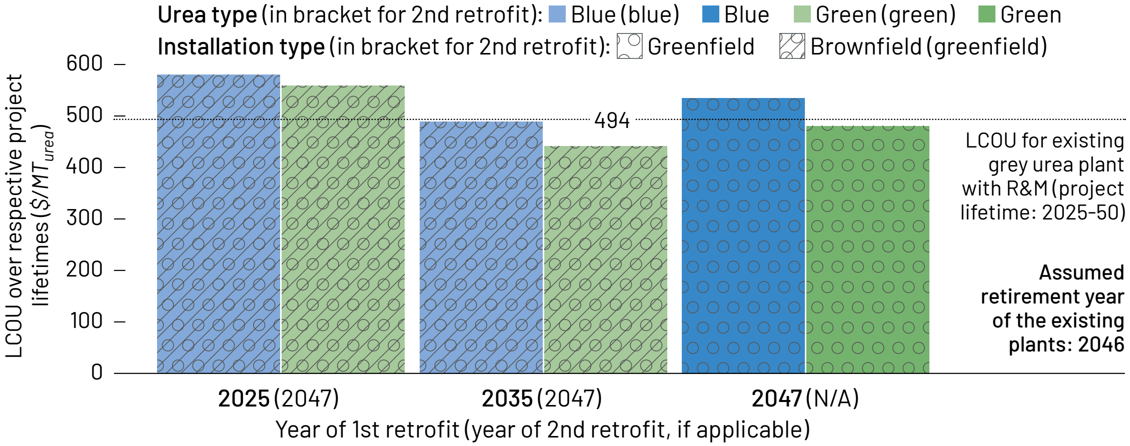
Source: iFOREST analysis

KRIBHCO Hazira

KRIBHCO Hazira, commissioned in 1986 and revamped in 2012, is the largest Urea plant in India, with a reassessed capacity of 2.194 MMT per annum for 2022-23. Over the past three years (2019-20, 2020-21, and 2021-22), its production levels were 2.33, 2.32, and 2.2 MMT, respectively. The plant's specific energy consumption was among the lowest in the country, ranging from 5.3 to 5.6 Gcal/MT Urea.

The lowest LCOU for this plant is achieved by operating on NG until 2035, then transitioning to a brownfield Green Urea plant, and finally shifting to a Greenfield Green Urea plant upon retirement. This scenario results in the LCOU at $441/MTUrea. The graph 4.8 illustrates the LCOU under various scenarios.

Graph 4.8: LCOU under different scenarios at KRIBHCO Hazira



Source: iFOREST analysis

In this category, the financially most viable route to decarbonisation is to transform these plants into Brownfield Green Urea in the year 2035 and then into Greenfield Green Urea when they retire. The only exception to this is RCF Thal, for which it is viable to transform to Brownfield Green Urea as early as 2030 and then follow the same path of transforming to Greenfield Green Urea on retirement.

4.4.2.5 Plants retiring between 2050-60 (PG4)

This category contains the following plants:

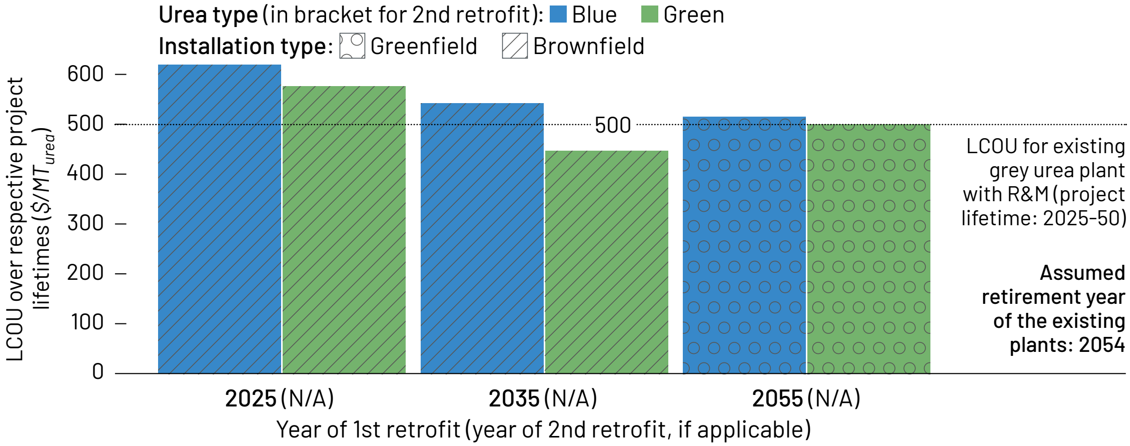
1. NFCL Kakinada I
2. CFCL Gadepan I
3. Yara, Babrala
4. KSFL Shajahanpur
5. IFFCO Aonla Expn.
6. NFL Vijaypur Expn.
7. IFFCO Phulpur Expn.
8. \NFCL Kakinada II
9. CFCL Gadepan II

The Urea plants in this group have up to 36 years of remaining plant operation (as of in 2024). The modelling results suggest that the most cost-effective route is to transition to Brownfield Green Urea in the year 2035. This is illustrated below using the examples of Yara and NFL Vijaypur Expn.

Yara, Babrala

Yara was commissioned in 1994 and has a reassessed capacity of 1.155 MMT per annum in 2022-23. The lowest LCOU for this plant is achieved by operating on NG until 2035, then transitioning to a brownfield Green Urea plant in 2035. This scenario results in the LCOU at $446/ MTUrea. The graph 4.9 illustrates the LCOU under various scenarios.

Graph 4.9: LCOU under different scenarios at Yara

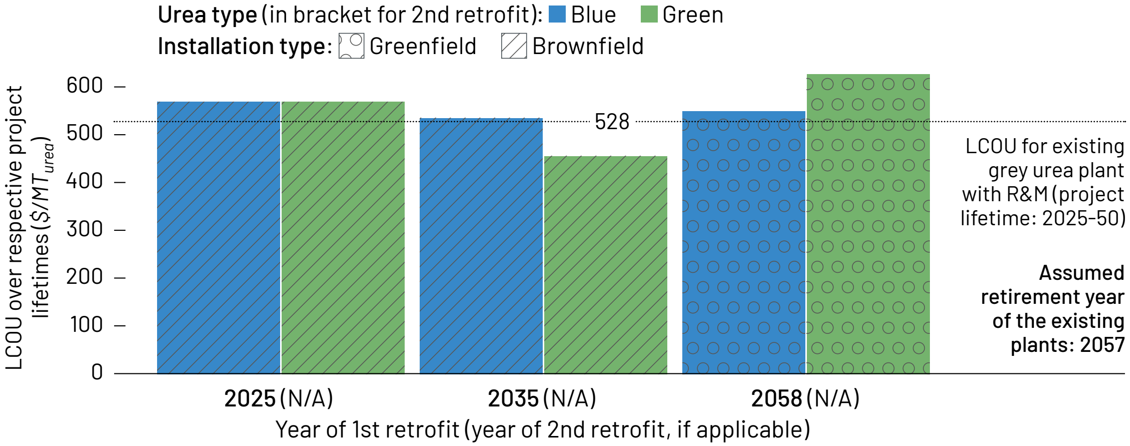


Source: iFOREST analysis

NFL Vijaypur Expn.

It was commissioned in 1997 and was revamped in 2012. Reassessed capacity in 2022-23 is 1.066 MMT per annum. The most economical strategy for this plant also is to shift to a brownfield Green Urea plant in 2035. This scenario results in the LCOU at $455/ MTUrea. The graph 4.10 illustrates the LCOU under various scenarios.

Graph 4.10: LCOU under different scenarios at NFL Vijaypur Expn.



Source: iFOREST analysis

In this category, it is observed that the financially most appealing route to decarbonisation is to transform these plants into Brownfield Green Urea in the year 2035 since they have too many years of service left (in which the initial investment must be recouped) to justify switching to and investing in a new Greenfield deployment by 2050.

4.4.2.6 Plants retiring after 2075 (PG5)

This group consists of the newest Urea plants with least 51 years of remaining plant operation (as of in 2024). The following plants come under this category:

1. CFCL Gadepan III
2. Matix Panagarh
3. HURL Gorakhpur
4. HURL Barauni
5. HURL Sindri
6. RFCL Ramagundam

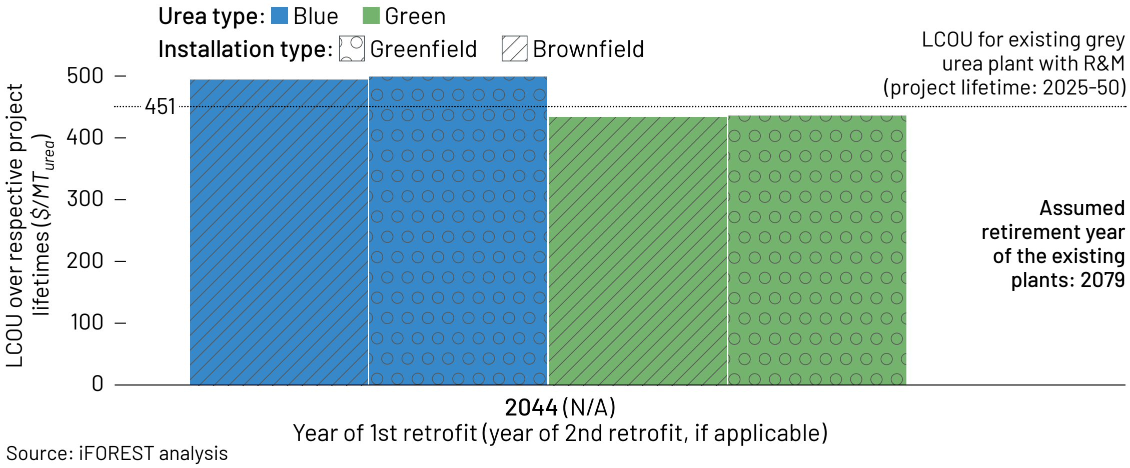
The modelling result indicates that it is most cost-effective to operate these plants until they reach an age of 25 years and then transition to Brownfield Green Urea. This is demonstrated below using the case of CFCL Gadepan III and HURL Barauni.

CFCL Gadepan III

It is a new plant that reports some of the best efficiencies in production. It was commissioned in the year 2019, its capacity is 1.27 MMT per annum (2022-23). According to the analysis of different scenarios as indicated in the graph 4.11, the most economical one is to operate the plant on NG till 25 years of the plant life and then retrofit it into brownfield Green Urea. The LCOU under this scenario is $443 / MTUrea.

For the plants retiring after 2050, it is observed that the financially most appealing route to decarbonisation is to transform these plants into Brownfield Green Urea.

Graph 4.11: LCOU under different scenarios at CFCL Gadepan III

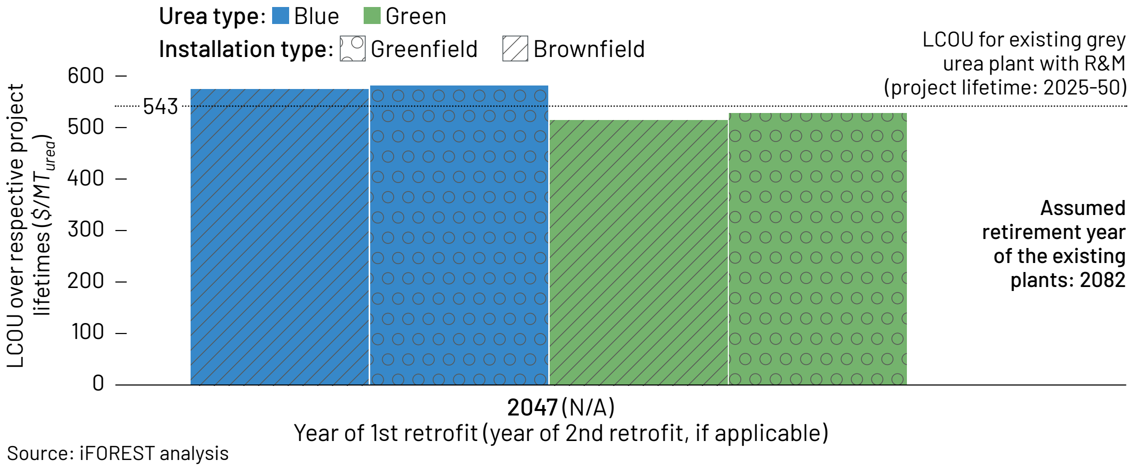


Source: iFOREST analysis

HURL Barauni

It is the newest plant in India and was commissioned in late 2022. Its capacity is 1.27 MMT per annum. According to the analysis of different scenarios as indicated in the graph 4.12, the most economical scenario is to operate the plant on NG till 25 years of the plant life and then retrofit it into brownfield Green Urea. The LCOU under this scenario is $514 / MTUrea.

Graph 4.12: LCOU under different scenarios at HURL Barauni



Source: iFOREST analysis

In all the plants under this category, it is observed that the most financially beneficial option is to operate the plants on NG for 25 years and then transform them into Brownfield Green Urea. However, the savings from choosing a Brownfield Green Urea deployment over a Greenfield Green Urea deployment are marginal. Blue Urea on the other hand remain significantly more expensive in both Greenfield and Brownfield scenarios.

4.5 Decarbonisation pathway

The results of plant-level modelling are similar to sectoral modelling. In both cases, it is economically prudent to move the entire fleet of urea manufacturing plants to Green Urea by 2050.

The plant-level modelling provides a clear roadmap for decarbonising urea manufacturing in India. The roadmap, henceforth called as the Green Urea Scenario, broadly classifies the existing plants into three categories:

Plants retiring during 2025-2040: There are 16 plants in this category, all with a capacity of less than 1.0 MMT per annum. The most economical approach for these plants is to transition to Greenfield Green Urea after retirement. Transitioning to Greenfield Grey or Greenfield Blue Urea is more expensive for these plants.

The LCOU for these plants varies significantly based on their specifications, performance until retirement, and the year of retirement. Generally, the LCOU is higher if the plant retires earlier. However, continuing the operation of these plants through R&M post-retirement is even more expensive.

Plants retiring between 2045-2050: There are just five plants in this category. The most cost-effective transition strategy for these plants is to first shift to Brownfield Green Urea during 2030-2035 and then to Greenfield Green Urea between 2045 and 2050. Continuing operations as Grey Urea plants after 2030-2035 is costly.

Plants retiring after 2050: There are 15 plants in this category. The most economical technology for these plants is to transition to Brownfield Green Urea. The timing of this shift depends on the age and performance of the existing plants. Generally, plants installed after 2020 should transition to Brownfield Green Urea after completing 25 years of operation. Those installed before 2000 should shift to Brownfield Green Urea between 2035-2040. The modelling results clearly show that continuing these plants as Grey Urea plants through R&M will be more expensive than transitioning to Brownfield Green Urea plants.

Overall, the most cost-effective urea for India post-2030 is Green Urea, as both Blue and Grey Urea are far more expensive.

Table 4.5: Decarbonisation schedule for existing Urea plants

Plant Name	Capacity (MMT/a)	Retirement year	Levelised cost ($/MT urea)	First Technology Transition		Second Technology Transition	
				Year	Technology	Year	Technology
GSFC Vadodara	0.37	2027	547	2025-2030	Greenfield Green Urea		
SFC Kota	0.38	2029	479	2030-2035	Greenfield Green Urea		
BVFCL Namrup II	0.24	2029	577	2025-2030	Greenfield Green Urea		
BVFCL Namrup III	0.27	2029	577	2025-2030	Greenfield Green Urea		
KFCL Kanpur	0.72	2030	490	2030-2035	Greenfield Green Urea		
MFL Chennai	0.49	2031	532	2030-2035	Greenfield Green Urea		
RCF Trombay	0.33	2033	504	2030-2035	Greenfield Green Urea		
IFFCO Kalol	0.545	2034	461	2030-2035	Greenfield Green Urea		
ZACL Goa	0.4	2034	488	2030-2035	Greenfield Green Urea		
MCF Manglore	0.425	2036	537	2035-2040	Greenfield Green Urea		
NFL Nangal	0.48	2038	502	2035-2040	Greenfield Green Urea		
NFL Panipat	0.51	2039	498	2035-2040	Greenfield Green Urea		
NFL Bhatinda	0.51	2039	502	2035-2040	Greenfield Green Urea		
SPIC Tuticorin	0.76	2039	551	2035-2040	Greenfield Green Urea		
IFFCO Phulpur I	0.7	2040	443	2035-2040	Greenfield Green Urea		
GNFC Bharuch	0.64	2042	449	2035-2040	Greenfield Green Urea		
RCF Thal	2.0	2045	550	By 2030	Brownfield Green Urea	2045-2050	Greenfield Green Urea
KRIBHCO Hazira	2.19	2046	441	By 2035	Brownfield Green Urea	2045-2050	Greenfield Green Urea

Table 4.5 continued

Plant Name	Capacity (MMT/a)	Retirement year	Levelised cost ($/MT urea)	First Technology Transition		Second Technology Transition	
				Year	Technology	Year	Technology
IGF Jagdishpur	1.1	2048	426	By 2035	Brownfield Green Urea	2045-2050	Greenfield Green Urea
NFL Vijaypur I	1.0	2048	442	By 2035	Brownfield Green Urea	2045-2050	Greenfield Green Urea
IFFCO Aonla I	0.8646	2048	456	By 2035	Brownfield Green Urea	2045-2050	Greenfield Green Urea
NFCL Kakinada I	0.5973	2052	414	2035-2040	Brownfield Green Urea		
TCL Babrala	0.8646	2054	432	2035-2040	Brownfield Green Urea		
CFCL Gadepan I	0.8646	2054	443	2035-2040	Brownfield Green Urea		
KSFL Shajahanpur	0.8646	2055	425	2035-2040	Brownfield Green Urea		
IFFCO Aonla II	0.8646	2056	437	2035-2040	Brownfield Green Urea		
IFFCO Phulpur II	1.0	2057	423	2035-2040	Brownfield Green Urea		
NFL Vijaypur II	1.0	2057	448	2035-2040	Brownfield Green Urea		
NFCL Kakinada II	0.5973	2058	426	2035-2040	Brownfield Green Urea		
CFCL Gadepan II	0.8646	2059	435	2035-2040	Brownfield Green Urea		
CFCL Gadepan III	1.2705	2079	442	2045-2050	Brownfield green Urea		
Matix	1.2705	2081	524	2045-2050	Brownfield green Urea		
HURL Gorakhpur	1.2705	2081	524	2045-2050	Brownfield green Urea		
RFCL Ramagundam	1.2705	2081	524	2045-2050	Brownfield green Urea		
HURL Barauni	1.2705	2082	524	2045-2050	Brownfield green Urea		
HURL Sindri	1.2705	2082	524	2045-2050	Brownfield green Urea		

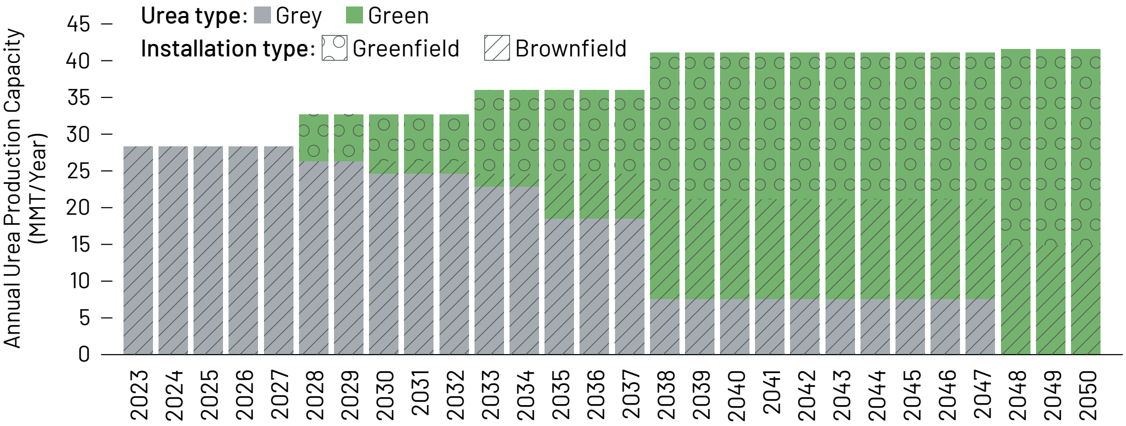
Source: iFOREST analysis

The advantages of the Green Urea Scenario over the other Scenarios are illustrated below.

4.6 Green Urea Scenario

Green Urea is the most economically viable option for the Indian Urea sector. If adopted as a policy, all existing Urea plants can be transitioned to Brownfield/ Greenfield Green Urea by 2050, as illustrated above. Additionally, production capacity will be enhanced as older, smaller plants are replaced with larger Green Urea plants.

Graph 4.13: Green Urea Scenario

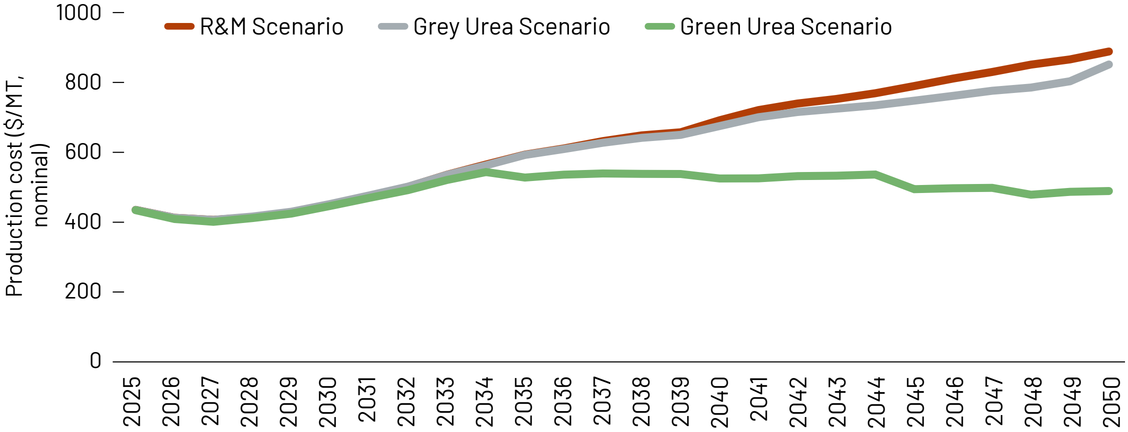


Source: iFOREST analysis

4.6.1 Cost of production

The LCOU for the Green Urea Scenario is $475/MT Urea compared to $550/MT Urea in the Renovation and Modernisation (R&M) Scenario and $540/MT Urea in the Grey Urea Scenario. This shows that continuing the practice of R&M to extend the life of existing Urea plants is the most expensive way to produce Urea in India. On the other hand, the cheapest Urea can be produced through the Green Urea route.

Graph 4.14: Nominal cost of production of Urea: 2025-2050

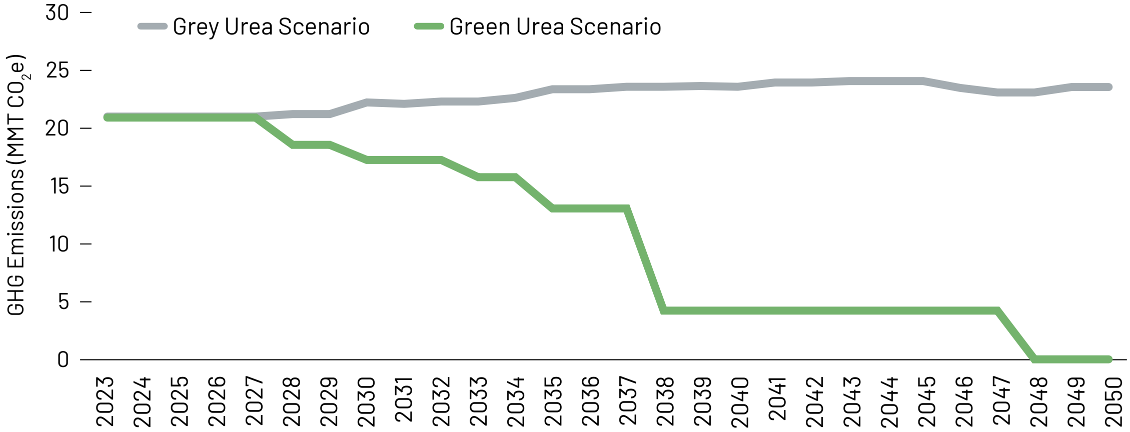


Source: iFOREST analysis

4.6.2 GHG Emissions

Current GHG emissions from Urea manufacturing are about 21 MMT CO_2e. Under the Grey Urea Scenario, this increases to 23.6 MMT CO_2e by 2050. However, in the Green Urea Scenario, GHG emissions from Urea production reach zero by 2050. The cumulative emissions saved by adopting Green Urea over Grey Urea are about 330 MMT CO_2e.

Graph 4.15: GHG Emissions during Urea Production: Grey vs. Green Urea Scenario



Source: iFOREST analysis

Apart from the reduction in the cost of Urea and GHG emissions, transitioning to Green Urea from the current Grey Urea production route will also reduce air and water pollution. While pollution costs have not been estimated in this study, reports show that groundwater pollution in and around Urea plants is significantly higher than drinking water standards.[8] Overall, the Green Urea Scenario has substantial economic and environmental advantages over the R&M or the Grey Urea Scenario.


Urea

05

Low Carbon Pathway for Urea Production and Consumption

The preceding sections have discussed the potential scenarios for Urea production and consumption in India by 2050. It is evident that different policy interventions and technological pathways will result in significantly different levels of Urea demand, GHG emissions, agricultural output, and subsidy burdens.

5.1 Low carbon pathway

The Low Carbon Pathway (LCP) for the Urea sector in India comprises the iFOREST Optimal Pathaway on the demand side and the Green Urea Scenario on the supply side. The LCP necessitates that governments adopt policies to increase areas under non-chemical farming, enhance Nitrogen Use Efficiency, promote other nitrogenous fertilisers, and implement a roadmap to transition existing Urea plants to Brownfield/Greenfield Green Urea.

Under the LCP, Urea production increases, consumption decreases, imports are eliminated, exports rise, subsidies are reduced, GHG emissions decline, and water and air pollution are mitigated. Additionally, both energy and food security are enhanced. The total economic and environmental benefit of adopting the LCP approaches a trillion dollars from 2025 to 2050.

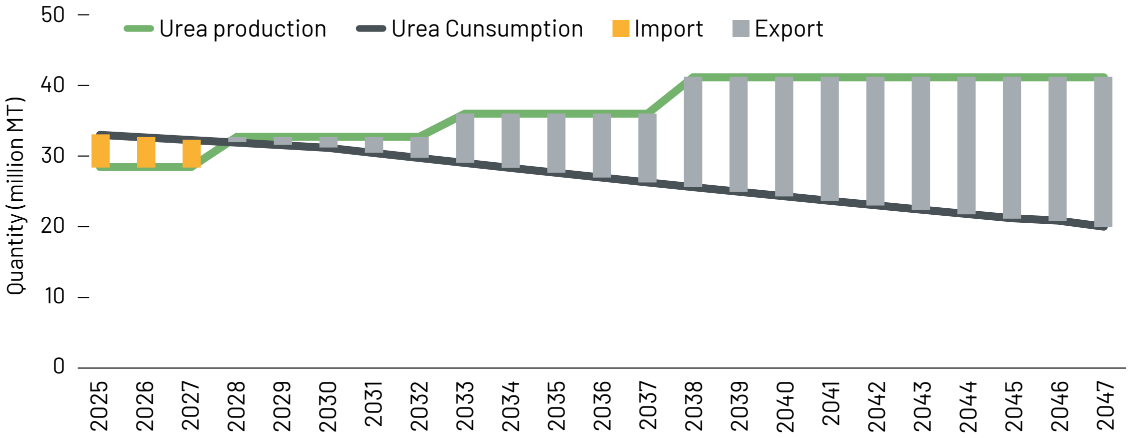
5.1.1 Production, Consumption, Imports and Exports

In the LCP, the production capacity (and maximum possible production) of Urea increases from 28.4 million metric tonnes (MMT) in 2022-23 to 41.5 MMT in 2050. The consumption of Urea reduces from 35.7 MMT in 2022-23 to 18.2 MMT. From importing 7.58 MMT Urea in 2022-23, India can potentially export 23.3 MMT/annum Green Urea by 2050.

The main economic advantages of the LCP over the BAU are:

1. The total Urea demand from 2025 to 2050 in the LCP is 675 MMT compared to 1058 MMT in the BAU. This 36% reduction in Urea demand translates into a saving of $250 billion.[1]
2. In BAU, India will have to import about 93 MMT of Urea during 2025-50, at a cost of $42 billion. In contrast, in the LCP, it can potentially export 290 MMT of Urea, earning an export revenue of $130 billion.[2]

Graph 5.1: Production, Consumption, Import and Export of Urea in the Low Carbon Pathway

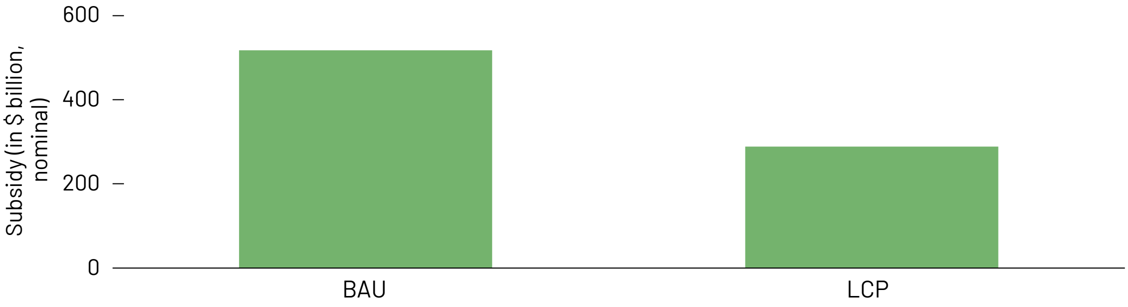


Source: iFOREST analysis

5.1.2 Urea Subsidy

In 2022-23, the Urea subsidy was equivalent to approximately 90% of the Urea cost. Assuming the subsidy level remains the same, the subsidy is likely to grow to $22.2 billion by 2050 under the BAU Scenario. In the LCP, the Urea subsidy in 2050 is projected to be just $7.8 billion – 65% lower than the BAU. The cumulative savings in subsidy during the 2025-50 period between BAU and LCP is a staggering $230 billion.

Graph 5.2: Cumulative Urea Subsidy – 2025-50: BAU vs. LCP



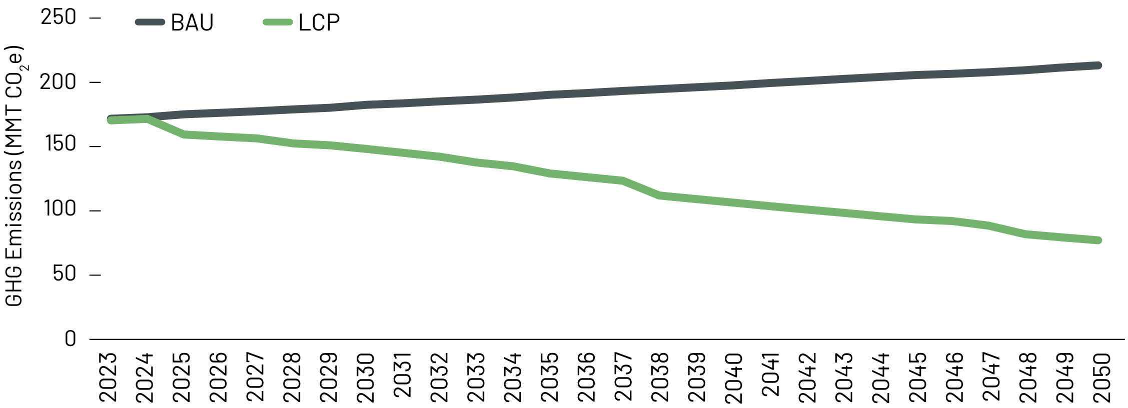
Source: iFOREST
Notes: BAU Scenario: Under this scenario, Urea production is based on the Grey Urea technology and the demand is based on iFOREST BAU Scenario.

5.1.3 GHG Emissions

The total GHG emissions from Urea production and use in India in 2022-23 were 171 MMT CO_2e. In the BAU Scenario, the total GHG emissions are projected to increase by 25% and reach 214 MMT CO_2e by 2050. In contrast, under the LCP, emissions in 2050 are projected to be only 77 MMT CO_2e – 64% lower than BAU and less than half of the current emissions.

The reduction in cumulative GHG emissions during 2025-2050 between the BAU and LCP is close to 1938 MMT CO_2e. Even at an average carbon price of $150 per tonne of CO_2 (likely a significant underestimation)[3], the savings in GHG emissions can be monetised to a value of $290 billion.

Graph 5.3: GHG Emission: BAU vs. LCP



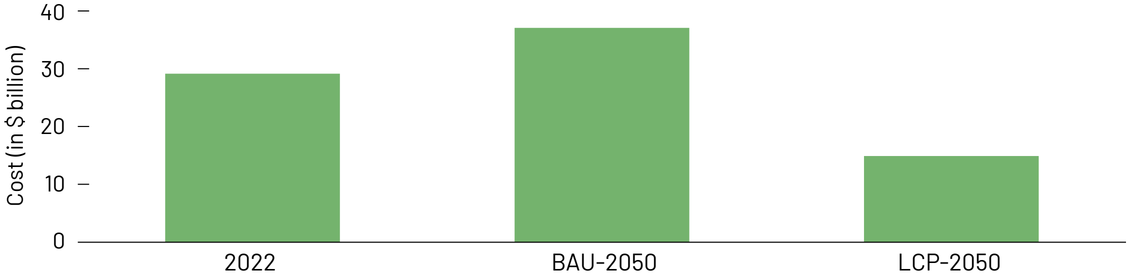
Source: iFOREST analysis

5.1.4 Water Pollution

The reduction in Urea consumption also means a significant decline in nitrate pollution of groundwater and surface water bodies, along with improvements in soil health and agricultural productivity. Although detailed estimates of these co-benefits are beyond the scope of this report, using estimates from the Indian Nitrogen Assessment published in 2017[4], an attempt has been made to extrapolate these co-benefits.

According to the Indian Nitrogen Assessment, the cost of water pollution to health and ecosystems due to Reactive Nitrogen (Nr) release into water bodies from nitrogenous fertiliser use was estimated at $3.9/kg Nitrogen in 2015. Assuming this cost remains the same (a gross underestimation), the cost of nitrogen pollution of water due to Urea use in India in 2022 can be estimated at $29 billion. In the BAU scenario, this cost is projected to rise to $37 billion in 2050. However, in the LCP, the cost of water pollution can be reduced by 60% in 2050 compared to the BAU scenario. The cumulative savings in health and ecosystem costs during the 2025-50 period in the LCP over the BAU is estimated at $315 billion.

Graph 5.4: Heath and Ecosystem Costs of Water Pollution Due to Urea



Source: iFOREST estimates based on The Indian Nitrogen Assessment, 2017

5.1.5 The Economic Case For a Low Carbon Pathway

There is a clear economic case for moving to a Low Carbon Pathway for the Urea sector. The total environmental and economic benefits amount to approximately $985 billion. This is also an underestimation as air pollution and land degradation costs have not been included.

Table 5.1: Economic and Environment Benefits of Adopting Low Carbon Pathway

	BAU Scenario	LCP	Savings
(i) Total Urea Consumption (MMT)	1058	675	383
(ii) Total Cost of Urea ($ billion)	570	320	250
(iii) Total Subsidy ($ billion)	515	285	230
(iv) Total GHG (MMT C_{02}e)	5382	3444	1938
(v) Carbon Cost ($ billion)	807	517	290
(vi) Water Pollution Cost ($ billion)	865	550	315
(vii) Imports (MMT)	93	0	93
(viii) Import savings ($ billion)	42	0	42
(ix) Export (MMT)	0	290	290
(x) Export Revenue ($ billion)	0	130	130
Total Savings in LCP over BAU ($ billion)			**985**

Source: iFOREST

5.2 The Way Forward

India has one of the most ambitious programmes to foster the growth of Green Hydrogen (H_2). The National Green Hydrogen Mission (NGHM) aspires to make India the global hub for the production, usage, and export of Green H_2 and its derivatives. With a target of 5 MMT of Green H_2 by 2030, the government has allocated ₹19,744 crore (approximately $2.5 billion) until 2029-30 to support this mission.[5]

Urea production is the second-largest consumer of hydrogen after oil refineries. In 2022-23, around 2.5 MMT of hydrogen was consumed by the Urea sector.[6] However, the Urea sector has shown little interest in the NGHM. In fact, the mission does not prioritise Urea, focusing instead on exports and domestic sectors such as steel, transport, and shipping.

This raises an important question: why is the Urea sector, whose production process is heavily reliant on hydrogen (the most energy-intensive process), not interested in Green H_2? The answer is not technological, as the technology to produce Green Urea from Green H_2 is available and established. Nor is it economic, as our modelling study indicates that the cheapest way to produce Urea in India is through the Green H_2 route. The issue lies in the management and operation of the Urea sector in the country.

A Controlled Sector

In India, the fertiliser subsidy is the second-largest subsidy after food, with nearly 60% allocated to Urea. In the 1970s, the Urea subsidy accounted for 10–20% of the production cost; now, it stands at 85-90%. This widening gap between production costs and retail prices, coupled with a significant increase in consumption, has caused the overall Urea subsidy to rise exponentially. Since the 1980s, the Urea subsidy has increased nearly 340 times at current prices (from less than ₹500 crore in 1980–81 to ₹168,692 crore in 2022–23).

Urea production is the second-largest consumer of hydrogen, yet it is not a priority sector in the National Green Hydrogen Mission.

Due to the subsidy regime, the Urea industry is one of the most controlled sectors in the country. Every aspect of Urea manufacturing is regulated, with subsidies provided separately for different cost components. Subsidies cover fixed costs such as salaries, wages, contract labour, marketing, repairs and maintenance, insurance, catalyst costs, and administrative expenses. Subsidy is also given for the variable costs, particularly natural gas (NG) prices, which fluctuate monthly. In addition to the tightly regulated subsidy system for Urea production, distribution and movement are also heavily controlled, with separate subsidies for freight and baggage costs.

The subsidy payment and movement control system is administered by a large central government bureaucracy. Besides the central bureaucracy, numerous personnel at state and district levels monitor the sale and supply of fertilisers and administer subsidies. This raises the crucial question: is the current system of control and regulation of Urea production and consumption suitable for the imperatives of food production and environmental sustainability in the 21st century?

The answer is evident. Besides the enormous burden on the central exchequer, the misuse and overuse of Urea are affecting soil health, food production, water quality, air quality, and indirectly energy security, as imports of NG and Urea have skyrocketed. In 2022-23, 84% of Urea was produced from imported NG, and 7.58 MMT of Urea (21% of total consumption) was imported.[7] Effectively, 87.5% of Urea consumed in the country was either based on imported NG or imported Urea. Most importantly, the current regime provides no incentive for the industry to innovate and grow.

The overall health of the Urea industry is poor. Even the profitability of the best-performing companies in the fertiliser sector is significantly lower than their peers in other core sectors of the economy. According to iFOREST's analysis for the years 2018-19 to 2021-22, the average net profit for the sector was below 5%. Consequently, there is neither spare capital nor interest in the industry to innovate, adopt new production techniques, or develop new products. This is precisely why the Urea industry has shown no interest in the NGHM.

A Green Urea Mission is good for the economy, environment and the farming community. The total economic and environmental benefits is close to a trillion dollars.

Decontrol the Urea Sector

The only way forward is to decontrol the sector and allow companies to compete in the market. Complete decontrol of Urea is possible if all subsidies are directly given to farmers through the Direct Benefit Transfer (DBT) route. This is not a new idea. In fact, the Shanta Kumar Committee, set up in 2014, recommended that farmers be given direct cash subsidies (about ₹7,000/ha), allowing the fertiliser sector to be deregulated.[8] Farmers would be free to choose crops and fertilisers as per their requirements, exercising discretion in the use of nitrogen (N), phosphorus (P), potassium (K) fertilisers, and even organic manures. The Urea industry, in turn, would compete in the market, bringing new technologies to reduce prices and improve efficiency.

A Green Urea Mission

Complementing the decontrol of the sector, the Government of India should launch a Green Urea Mission with the 2050 targets of:

1. Increasing the area under non-chemical farming to 30%.
2. Improving nitrogen use efficiency by 30%.
3. Reducing the proportion of urea in nitrogenous fertilisers by 30%.
4. Transitioning the entire urea manufacturing sector to Green Urea.

As illustrated above, the economic and the environmental benefit of this transition is close to a trillion dollars.

Annexures

ANNEXURE 1

Green Hydrogen Production Technologies

H_2 can be produced renewably from water using technologies such as the Solid Oxide Electrolyser Cell (SOEC), Proton Exchange Membrane (PEM) and Alkaline Water Electrolyser (AWE) and Anion Exchange Membrane Water Electrolyser (AEM)

This report finds Alkaline Water Electrolysers technology to be the best fit. This is due to the following reasons:

- **Efficiency:** Higher demonstrated electrical efficiency in comparison to other electrolyser technology. Other methods may yield higher efficiency in the future but not at present[1].
- **Renewable and inexpensive nature of electrolyte inputs:** These are primarily water, sodium hydroxide, potassium hydroxide[2].
- **Low cost:** While the cost of producing hydrogen using different electrolysers is expected to approach each other in the long run, Alkaline Electrolysers represent a significantly less expensive option until 2030 at the earliest.
- **Low cost of catalysts:** Uses commonly available materials such as Nickel, Cobalt, Iron, and Carbon[3]. This is opposed to the platinum and gold catalysers that other methods require.
- **Mature Technology:** Currently provides two-thirds of global electrolyser capacity[4].
- **Long life of the stack:** 60,000-100,000 hours as opposed to 20,000-60,000 of closest competitor (PEM)[5].

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[1] Price. F. et. al. (2023), Scoping report on material requirement for a UK hydrogen economy, British Geological Survey open report. OR/23/017. https://nora.nerc.ac.uk/id/eprint/535121/1/OR23017.pdf

[2] ibid

[3] ibid

[4] Anon. IEA. 2022. "Electrolysers". Paris: International Energy Agency. https://www.iea.org/reports/electrolyser

[5] Price. F. et. al. (2023), Scoping report on material requirement for a UK hydrogen economy, British Geological Survey open report. OR/23/017. https://nora.nerc.ac.uk/id/eprint/535121/1/OR23017.pdf

Table 1: Comparison of Electrolysers

Characteristics	Alkaline Water Electrolyser			PEM			SOEC			AEM
Operating Temperature	60 – 90º C			50 – 80º C			650 – 1,000º C			50 – 60º C
Operating Pressure	1 – 30 bar			30-80 bar			1 bar			1 – 30 bar
Stack life (hours) (2019, 2030, Long term)	60-90k	90-100k	100-150k	30-60k	60-90k	100-150k	10k-30k	40-60k	75-100	-
Technology readiness level (TRL) out of 11 (where numbers beyond 9 indicate that the technology is being further optimised)	9, Market uptake			9, Market uptake			7, Demonstration			6, Large prototype
Electrical Efficiency % (2019, 2030 and Long Term)[6]	63-70	65-71	70-80	56-60	63-78	67-74	74-81	77-84	77-90	--
CAPEX ($/KWe)	500-1,400	400-850	200-700	1,100-1,800	650-1,500	200-900	2,800-5,600	800-2,800	500-1,000	

Source: Adopted from The Future of Hydrogen - Seizing today's opportunities. June 2019. International Energy Agency (IEA).

ANNEXURE 2

Technologies for Nitrogen production

Globally, N_2 is most often obtained at scale through the use of Cryogenic Air Separation Units– a developed and mature technology. A survey of available technology options for N_2 production suggest that the Urea industry's N_2 would also be best met by an Air Separation Unit (ASU) or Cryogenic Distillation.

This method involves the removal of dust and other undesired substances from air before it is liquified under high pressure and low temperatures. The different temperatures at which the constituent compounds and elements volatilise are used to distil this liquified ambient air into N_2.

The primary advantage of ASUs using Cryogenic Distillation for Green Urea over alternatives is the quantity of output it is suitable for.

- Pressure Swing Absorption (PSA) for 25 to 800 Nm^3/hour
- Membrane Permeation for 3 to 3000 Nm^3/hour
- Cryogenic distillation or Air Separation Unit (ASU) for 250 to 50,000 Nm^3/hour

Since India's Urea plants require an average of ~34,000 Nm^3/hour of N_2, only Cryogenic distillation can supply these quantities. Further, Cryogenic air separation units are usually able to achieve higher levels of N_2 purity than

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[6] Anon. 2019. The Future of Hydrogen - Seizing today's opportunities. International Energy Agency. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

non-cryogenic methods[7]. A comparison of different technologies of nitrogen production has been done in the table below.[8]

Table 1: Comparison of Electrolysers

	ASU (Cryogenic)	PSA	Membrane
Temperature, °C	(-195 to -170)	20-35	40-60
Pressure, bar	1-10	6-10	6-25
Purity (wt. %)	99.999	99.8	99.5
Energy consumption, kWh/kg N_2 (GJ/ton NH_3)	0.1 (0.3)	0.2-0.3 (0.7-1)	0.2-0.6 (0.7-2)
Capacity range (Nm^3/h)	250-50,000 High	25-3,000 Medium	3-3,000 Low
Load range, %	60-100	30-100	30-100
Investment cost (k€/ tpd NH_3)	<8	4-25	25-45
TRL	9	9	8-9

Source: Adopted from Islanded ammonia power systems: Technology review & conceptual process design. October 2019. Renewable and Sustainable Energy Reviews

ANNEXURE 3

Carbon Capture Technologies

In the conventional method of producing (Grey) Urea, the CO_2 generated during Ammonia synthesis is collected and made to react with Ammonia under specific conditions to produce Urea. However, since the entire SMR process is eliminated in the production of Green Urea and H_2 is no longer obtained from NG, this source of CO_2 is no longer available. Further, since this bid for decarbonisation also assumes that renewable electricity is being utilised, even the captive power plant no longer generates CO_2.

Thus, there is a need to identify a reliable source of CO_2. This CO_2 will first need to be cleaned of contaminants such as other gases and particulate matter before it is usable. In addition, it will need to be of a high enough volume to be commercially viable for use in Urea manufacturing. Consequently, the most suitable sources are those industries that are currently struggling to reduce their emissions. This use of externally sourced CO_2 allows the Urea industry to act as a carbon sink, i.e., effectively become carbon-negative and earn carbon credits that can be sold.

As the illustration below shows, emissions in the Indian industry are primarily from the generation of Power, Iron and Steel industries, Cement Manufacturing, and Oil and Gas Refineries.

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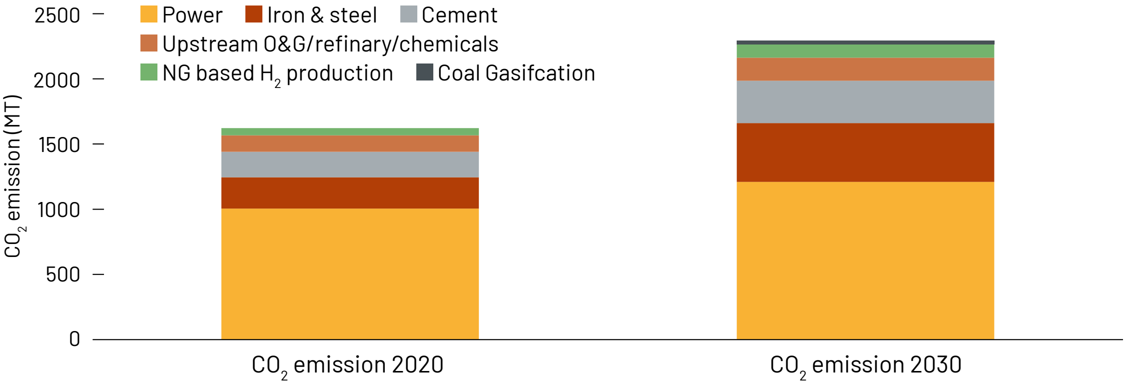
[7] Air Separation Process Technology and Supply System Optimisation Overview, universal Industrial Gases. http://www.uigi.com/compair.html

[8] Rouwenhorst, Kevin H.R.; van der Ham, Aloijsius G.J.; Mul, Guido; Kersten, Sascha R.A. (2019): Islanded ammonia power systems: Technology review & conceptual process design. In Renewable and Sustainable Energy Reviews 114, p. 109339. DOI: https://doi.org/10.1016/j.rser.2019.109339.

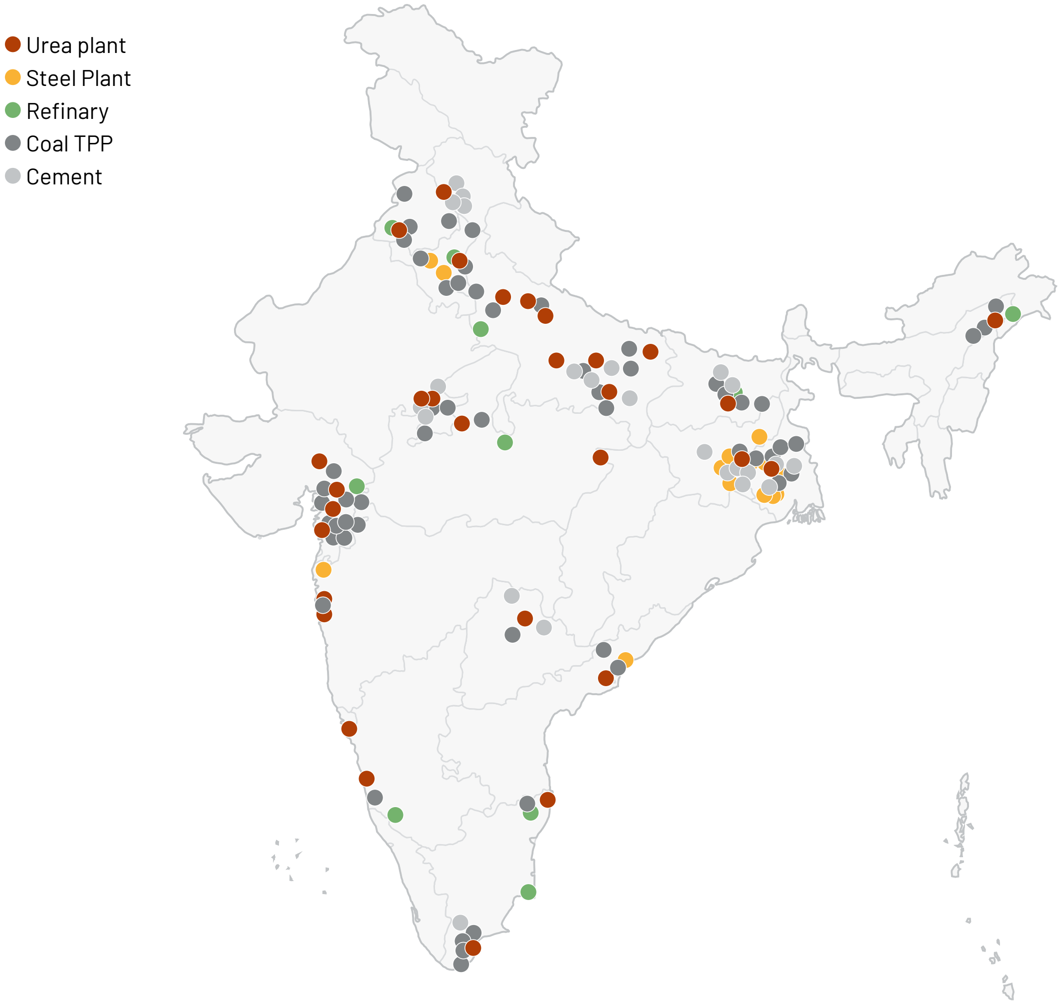
Graph 1: Sector-wise CO_2e Emissions Historic (2020) vs Projected (2030)



Source: Carbon Capture, Utilisation and Storage (CCUS), Policy Framework and its Deployment Mechanism in India, November 2022, Niti Aayog

Fortunately, each of the 36 Urea plants in India has one or more industrial units of the above industrial sectors within a 150 km radius. This will ensure that the cost of supplying piped CO_2 from emitters to Urea plants is not prohibitively high.

Map 1: Illustration of CO_2 emitting plants within 150 km of Urea Plants



Source: iFOREST Analysis

Table 1: Major CO_2 emitting plants in vicinity of Urea Plants

Urea plant	Location	Industry	Name of the plant	Capacity		Distance (KM)
				Unit	Value	
National Fertilizers Limited (NFL), Nangal-II	Nangal, Punjab	Thermal power	Rajpura thermal power (NPL)	MW	1,400	121
		Thermal power	Goindwal Sahib Power Plant	MW	540	150
		Cement	BAGA CEMENT WORKS, Solan, Himachal	MMTPA	6	100
		Cement	Gagal Cement Works-I&II (ACC Cement), Barmana, Himachal	MMTPA	5.5	80
National Fertilizers Limited (NFL), Bhatinda	Bhatinda, Punjab	Thermal power	Talwandi Sabo power (TSPL)	MW	1,980	50
		Thermal power	Guru Hargobind Thermal Plant	MW	920	30
		Thermal power	Rajiv gandhi TPP	MW	1,200	150
		Refinery	GURU GOBIND SINGH REFINERY (HMEL)	MMTPA	11.3	50
National Fertilizers Limited (NFL), Panipat	Panipat, Haryana	Thermal power	Deenbandhu chhotu ram TPP	MW	600	110
		Thermal power	Jhajjar Power Ltd	MW	1,320	140
		Thermal power	Panipat Thermal Power plant	MW	710	12
		Thermal power	Indira gandhi TPP	MW	1,500	140
		Thermal power	NTPC dadri (Coal based)	MW	1,460	125
		Steel Plant	Jindal Stainless Hisar Steel Plant	MMTPA	0.8	150
		Refinery	PANIPAT REFINERY (IOCL)	MMTPA	15	20
National Fertilizers Limited (NFL), Vijaipur and Vijaypur Expn.	Vijaypur, Madhya Pradesh	Thermal power	Jaypee Bina Thermal Power plant	MW	500	150
		Refinery	BINA REFINERY	MMTPA	7.8	120
Brahmaputra Valley Fertilizer Corporation Limited	BVFCL, Namrup II and III	Thermal power	Namrup Thermal Power Station	MW	98.5	5
		Thermal power	Lakwa Replacement Power Plant	MW	69.3	55.5
		Refinery	DIGBOI REFINERY	MMTPA	0.65	40
Rashtriya Chemicals and Fertilizers Limited (RCF), Trombay-V	Trombay, Maharashtra	Thermal power	Tata Power Trombay Thermal Power Plant	MW	250	100
		Refinery	MUMBAI REFINERY (BPCL)	MMTPA	12	3
		Refinery	MUMBAI REFINERY (HPCL)	MMTPA	9.5	3
Rashtriya Chemicals and Fertilizers Limited (RCF), Thal	Thal, Maharashtra	Thermal power	Tata Power Trombay Thermal Power Plant	MW	250	100
		Steel plant	JSW Dolvi Steel Works	MMTPA	5	22
		Refinery	MUMBAI REFINERY (BPCL)	MMTPA	12	80
		Refinery	MUMBAI REFINERY (HPCL)	MMTPA	9.5	80
Madras Fertilizers Limited (MFL), Chennai	Chennai, Tamil Nadu	Thermal power	Vallur Thermal Power Station	MW	1500	12
		Refinery	MANALI REFINERY (CPCL)	MMTPA	10.5	6
		Refinery	NAGAPATTNAM REFINERY (CPCP)	MMTPA	1	20

Table 1 continued

Urea plant	Location	Industry	Name of the plant	Capacity		Distance (KM)
				Unit	Value	
Indian Farmers Fertiliser Cooperative (IFFCO), Kalol	Kalol, Gujarat	Thermal power	Wanakbori Thermal Power Station	MW	800	120
		Refinery	GUJARAT REFINEY (IOCL)	MMTPA	13.7	120
Indian Farmers Fertiliser Cooperative (IFFCO), Phulpur and Phulpur Expn.	Phulpur, Uttar Pradesh	Thermal power	Prayagraj Thermal Power Plant	MW	1980	68
		Thermal power	Unchahar Thermal Power Plant	MW	1550	110
		Thermal power	Meja Thermal Power Station	MW	1320	49
		Cement plant	Jaypee Cement Factory, Chunar, Uttar Pradesh	MMTPA	2.5	120
		Cement plant	ACC Cements, Tikariya, Uttar Pradesh	MMTPA	2.64	98
Indian Farmers Fertiliser Cooperative (IFFCO), Aonla and Aonla Expn.	Aonla, Uttar Pradesh	Thermal power	Harduaganj Thermal Power Plant	MW	1270	150
		Thermal power	Roza Thermal Power Plant	MW	1200	106
Krishak Bharati Cooperative	KRIBHCO, Hazira	Thermal power	Surat Lignite TPS	MW	250	58.5
		Thermal power	NTPC Kawas Power Plant	MW	4000	4
		Thermal power	Salaya Thermal Power Plant	MW	1200	15
		Steel plant	Arcelormittal Nippon Steel Plant	MMTPA	9.6	14
		Refinery	GUJARAT REFINEY (IOCL)	MMTPA	13.7	150
Gujarat State Fertilizers and Chemicals Ltd (GSFC), Vadodara I & II	Vadodara, Gujarat	Thermal power	Wanakbori Thermal Power Station	MW	800	85
		Thermal power	DGEN MEGA Thermal Power Plant	MW	1200	136
		Steel plant	Arcelormittal Nippon Steel Plant	MMTPA	9.6	150
		Refinery	GUJARAT REFINEY (IOCL)	MMTPA	13.7	10
Shriram Fertilisers & Chemicals (SFC), Kota	Kota, Rajasthan	Thermal power	Kota TPP	MW	1241	6
		Thermal power	Kalisindh TPP	MW	1200	90
		Thermal power	Kawai TPP	MW	1320	120
		Cement plant	Shriram Cement Works, Kota	MMTPA	4	3
		Cement plant	Manglam cement, Morak Kota	MMTPA	3.25	60
Kanpur Fertilizers & Chemicals Limited (KFCL), Kanpur	Kanpur, Uttar Pradesh	Thermal power	Unchahar Thermal Power Plant	MW	1550	150
		Cement plant	Birla Cement Factory, Raebareli, Uttar Pradesh	MMTPA	1.3	120
		Cement plant	ACC Limited, Tikariya, Uttar Pradesh	MMTPA	2.64	150
Zuari Agro Chemicals LTD (ZACL), Goa	Zuarinagar, Goa					

Table 1 continued

Urea plant	Location	Industry	Name of the plant	Capacity		Distance (KM)
				Unit	Value	
Southern Petrochemical Industries Corporation Ltd (SPIC), Thoothukudi	Thoothukudi, TamilNadu	Thermal power	Tuticorin Thermal Power Plant	MW	300	10
		Thermal power	Muthiara Thermal Power Plant	MW	1200	30
		Thermal power	ITPCL Thermal Power Plant	MW	1200	8
		Thermal power	SEPC Thermal Power Plant	MW	525	6
		Cement plant	The Ramco Cements, Ramaswamy Raja Nagar, Virudhnagar, Tamilnadu	MMTPA	3	102
Mangalore Chemicals & Fertilizers (MCF), Mangaluru	Mangaluru, Karnataka	Thermal power	Udupi Power Corporartion Limited	MW	1200	33
		Cement plant	Chettinaad Cement Plant, Kallur, Karnataka	MMTPA	2.5	54
		Refinery	MANGALORE REFINERY (MRPL)	MMTPA	15	14
Gujarat Narmada Valley Fertilizers & Chemicals Limited (GNFC), Bharuch	Bharuch, Gujarat	Thermal power	Ukai Thermal Power Plant	MW	500	120
		Thermal power	Surat Lignite TPS	MW	250	57
		Thermal power	DGEN MEGA Thermal Power Plant	MW	1200	46
		Steel plant	Arcelormittal Nippon Steel Plant	MMTPA	9.6	100
		Refinery	GUJARAT REFINERY (IOCL)	MMTPA	13.7	80
Indo Gulf Fertilisers (IGF), Jagdishpur	Jagdishpur, Uttar Pradesh	Thermal power	NTPC Tanda	MW	1760	113
		Thermal power	Unchahar Thermal Power Plant	MW	1550	85
		Cement plant	ACC limited, Tikariya , Uttar Pradesh	MMTPA	2.64	53
Nagarjuna Fertilizers and Chemicals Limited (NFCL), Kakinada-I and II	Kakinada, Andhra Pradesh	Thermal power	NTPC Simhadri Thermal Power Plant	MW	1000	140
		Steel plant	Vizag Steel Plant	MMTPA	7.3	150
		Refinery	VISHAKHAPATNAM REFINERY (HPCL)	MMTPA	11	150
		Refinery	TATIPAKA REFINERY (ONGC)	MMTPA	0.07	70
Chambal Fertilisers and Chemicals Limited (CFCL), Gadepan I, II and III	Gadepan, Rajasthan	Thermal power	Kota TPP	MW	1241	40
		Thermal power	Giral TPP	MW	2320	126
		Thermal power	Kawai TPP	MW	1320	84
		Cement plant	Shriram Cement Works, Kota	MMTPA	4	38
Yara Fertilisers India Pvt Ltd, Babrala	Babrala, Uttar pradesh	Thermal power	Harduaganj Thermal Power Plant	MW	1270	64
		Thermal power	NTPC Dadri	MW	2650	100
		Refinery	MATHURA REFINERY (IOCL)	MMTPA	8	150
Kribhco Shyam Fertilizers Limited (KSFL), Shahjhanpur	Shahjhanpur, Uttar Pradesh	Thermal power	Roza Thermal Power Plant	MW	1200	10

Table 1 continued

Urea plant	Location	Industry	Name of the plant	Capacity		Distance (KM)
				Unit	Value	
Matix Fertilizers and Chemicals Ltd, Panagarh	Panagarh, West Bengal	Thermal power	Sagardighi Thermal Power Station	MW	1600	150
		Thermal power	Durgapur Steel thermal Power Station	MW	1000	36
		Thermal power	Mejia Thermal Power Station	MW	1710	44
		Steel plant	JSW Bengal Steel Salboni Plant	MMTPA	10	118
		Steel plant	Jai Balaji Steels Purulia Plant	MMTPA	5.4	41
		Steel plant	SAIL Durgapur Steel Plant	MMTPA	5.3	28
		Cement plant	Birla Cement Works (Durgapur Cement Works)	MMTPA	2.3	31
		Cement plant	JSW Cement works, Salboni, West Bengal	MMTPA	3.6	115
Hindustan Urvarak & Rasayan Limited (HURL), Barauni	Barauni, Bihar	Thermal power	Barauni Thermal Power Station	MW	720	4
		Thermal power	Barh Thermal Power Station	MW	2640	43
		Cement plant	DDSPL, Kalyanpur Bihar	MMTPA	1.15	115
		Cement plant	Shivay Pvt Ltd, Sirsamal, Bihar	MMTPA	3.6	150
		Refinery	BARAUNI REFINERY (IOCL)	MMTPA	6	15
Hindustan Urvarak & Rasayan Limited (HURL), Sindri	Sindri, Jharkhand	Thermal power	Maithon Thermal Power Plant	MW	1050	50
		Thermal power	Bokaro TPP	MW	500	80
		Thermal power	Chandrapura TPP	MW	500	100
		Steel plant	TATA Steel Jamshedpur Steel Plant	MMTPA	10	133
		Steel plant	ESL Steel Plant	MMTPA	2.57	31
		Steel plant	SAIL Bokaro Steel Plant	MMTPA	4.65	55
		Cement plant	Nuvoco Vistas Crp Ltd, Jojobera, Jharkhand	MMTPA	4.6	144
Hindustan Urvarak & Rasayan Limited (HURL), Gorakhpur	Gorakhpur, Uttar Pradesh	Thermal power	NTPC Tanda	MW	1760	116
Ramagundam Fertilizers Chemicals (RFCL), Ramagundam	Ramagundam, Telangana	Thermal power	Ramagundam TPP	MW	2600	9
		Cement plant	Kesoram Cement Factory, Basant Nagar, Telangana	MMTPA	1.2	20
		Cement plant	Orient Cement, Devpur, Telangana	MMTPA	8	56

Source: iFOREST analysis

Due to the varied nature of emissions streams from these industries, a blanket recommendation regarding the carbon capture and utilisation (CCU) technology to be used is unlikely to be helpful. Each industry and industrial unit will need to evaluate the relative merits of different available technologies and make a selection based on their requirements.

The five most developed technologies have different drawbacks and advantages that are discussed in detail below. They are optimised for different conditions and outcomes, such as:

- The temperature of the emissions stream
- The pressure of the emissions stream
- The volume of emissions stream
- The purity of captured CO_2
- The concentration of CO_2
- The energy consumption
- The cost of operation

Research indicates that Chemical Solvent Absorption and Pressure Swing Adsorption are the most mature and appropriate technologies for the considered industries. Below is a comparison of the different available technologies[9].

Table 2: Comparison of Carbon Capture Technologies

Technology	Mechanisms	Pros	Cons
Chemical Solvent Absorption	• Chemical reaction between a solvent and CO_2 • Governed by: Rate kinetics & thermodynamics. • Suitable for: Post-combustion method	• High capacity at low CO_2 pressure • Selective capture and • High purity CO_2 product • Mature technology	• Energy-intensive regeneration • Low absorption–desorption rate • Corrosion • Absorbent degradation • High operating cost
Physical Solvent Absorption (PSA)	• Absorption due to solubility of CO_2 in a solvent • Governed by: Henry's Law • Suitable for: Pre-combustion method	• High capacity at low temperature and high CO_2 pressure • Regeneration through low temperature flashing or pressure reduction • High absorption capacity & lower solvent recirculation rates • Cheaper solvent • Mature technology	• Low selectivity • High energy consumption • Low capacity at high temperature and low pressure • Absorbent loss
Adsorption	• Selective adsorption due to difference in diffusivity & heat of adsorption • Governed by: Pressure change. • Suitable for: Both Pre & Post-combustion method	• High capacity at low temperature and high pressure • Low waste generation	• Low CO_2 selectivity • Capacity decreases with temperature • Normally require high pressure • Moisture degrades the adsorbent performance. • Batch process • High electrical energy consumption

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[9] Anon. (2022) Carbon Capture Utilisation and Storage (CCUS) – Policy Framework and Deployment Mechanism in India P-139, NITI Aayoga https://www.niti.gov.in/sites/default/files/2022-12/CCUS-Report.pdf

Table 2 continued

Technology	Mechanisms	Pros	Cons
Membrane separation	• Different gas permeability • Governed by: Difference in concentration. • Suitable for: Pre-combustion method	• Relatively low operation cost • Easy handling and Operation	• High manufacturing cost • Relatively low separation selectivity • Permeability still low • Negative effect of moisture
Cryogenic separation	• Low-temperature separation through liquefaction • Governed by: Temperature change. • Suitable for: Post-combustion method	• Selective capture and high capture efficiency (up to 99.9%) • Liquefied CO_2 product • Food grade CO_2 • Almost no steam consumption • Low area footprint	• High energy requirement • Low efficiency • Moisture pre-removal is required. • Solidified CO_2 may be accumulated on the surface of heat exchanger

Source: Carbon Capture Utilisation and Storage (CCUS) – Policy Framework and Deployment Mechanism in India, November 2022. Niti Aayog

Table 3: CCU in different industries

Sector	Ref. Plant Capacity	CCU Capacity	Recommended technology	Electricity Consumption, kWh/TCO_2	Total Capital Costs INR Crore	Total Cash (Variable/ Non-Capital) Costs, ₹/TCO_2	Total Cost ₹/TCO_2
Cement	2.5mtpa clinker	2 mtpa	PSA + Cryogenic	340-370	1,600-1,800	1,050-1,600	1,800-1,600
Iron and Steel	2.0 mtpa BF-BOF based ISP	2 mtpa	E-RWGS (Reverse Water Gas Shift)	170-190	1,600-2,000	1,900-2,300	2,900-3,600
Refinery (CDU and FCC)	5 mpta crude processing	1 mtpa	Amine Based Capture (Chemical Solvent Absorption)	110-130	1,100-1,300	2,700-3,100	3,900-4,500
Coal Based Power	800 MW	5mtpa	Amine based capture (Chemical Solvent Absorption)	250-300	3,500-4,000	2,100-2,500	2,800-3,500

Source: Carbon Capture Utilisation and Storage (CCUS) – Policy Framework and Deployment Mechanism in India, November 2022. Niti Aayog

ANNEXURE 4

Techno-economic modelling

The success with which shifts in technology are adopted in the Urea industry will hinge upon both the accessibility of new technologies and the financial implications of making these transitions. In this study, the technologies whose use is being advocated for are available (or likely to be available by 2025) and thereby accessible. The modelling, therefore, has focussed on economic aspects, especially to calculate the Levilised Cost of Urea (LCOU) during different technology transition scenarios.

1. Methodology

The voluntary decarbonisation of the fertiliser industry will be chiefly driven by economics. Therefore, economic modelling using various scenarios was undertaken to assess the decarbonisation pathways for the fertiliser industry in India. The economic analysis has been divided into the following two sections:

a). Sectoral analysis

The main objective of this analysis is to get a broader view of economic feasibility of decarbonisation in India using a central planner's perspective, wherein the decision of retrofitting/decommissioning a current plant or replacing it with a Greenfield plant is taken based on a country-level cost analysis. Under this, a techno-economic analysis of all the 34 fully operational Urea plants[10] in India for an optimisation period of 2025-2050 was performed, using Levelised Cost of Urea (LCOU) as the key parameter, in order to find the most cost-effective production pathway while also meeting India's future Urea demand. Furthermore, through the use of different scenarios, we also assess the impact of variations in future cost development for technologies and commodities that are critical for decarbonisation. This is an optimisation model with a cost-minimisation objective function, in which for given techno-economic parameters, the model estimates the most cost-optimal way of meeting the country's Urea demand by, for example, shutting down the most energy-inefficient plant(s) and/or retrofitting certain Urea plants to Blue/Green Urea production techniques, in case the model deems it to as cheaper than letting them operate using the Grey Urea technique.

As already mentioned, the optimisation horizon for this analysis is 2025-2050. The Urea demand projection is based on "iFOREST Optimal". Regarding import and export assumptions, no Urea import is considered for the entire optimisation horizon, which is in line with India's goal of achieving self-sufficiency in Urea by 2025[11]. Based on historical trade data, a Urea export of up to 5% of the annual demand is allowed in the model. Regardless of the year, a constant export revenue of 450 $/t_urea is assumed[12]. Each of the currently operating Urea plants in India

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[10] India has 36 plants. But two plants — Brahmaputra Valley Fertilizer Corporation Limited: Namrup-II and III — were excluded as they were not operational or partially operational during the study period

[11] Business Today (2022): India to become 'aatmanirbhar' in Urea production by 2025 end, says Mandaviya. Available online at https://www.businesstoday.in/industry/agriculture/story/india-to-become-aatmanirbhar-in-Urea-production-by-2025-end-says-mandaviya-340419-2022-07-05, checked on 3/21/2024

[12] Fertiliser India (2021): Urea Imports and Weighted Average of Import Price in India during 2021-22. Available online at https://fertiliserindia.com/Urea-imports-and-weighted-average-of-import-price-in-india-during-2021-22/#:~:text=India%20imported%2039.7%20Lac%20tons,ton%2C%20in%20September%2C%2021, checked on 3/21/2024.

is modelled to be allowed a retrofit to Blue or Green Urea technique. For any new installation (Greenfield plant), either to meet additional Urea demand or to replace an inefficient current Urea plant, it can be based on either Grey, Blue or Green Urea technique. The techno-economic parameters for these Greenfield plants are based on Hindustan Urvarak & Rasayan Limited (HURL), Sindri, the newest plant for which operational data is available. The optimisation model's objective is to minimise the overall system costs over the entire period from 2025 to 2050. It should be noted that inflation is not considered in this analysis. Furthermore, to assess the impact of uncertainty in future cost development for crucial technologies and commodities, we have modelled the following three scenarios.

- **Median scenario:** This scenario assumes a "middle way" for future cost developments. In case of electrolyser, we assume the average value of the cost range provided by IEA. For the NG cost projection, we use the reference case of US Henry Hub NG price projections. Green electricity costs are assumed to be similar to the Round The Clock (RTC) RE supply contracts signed in India in the last few years (0.0575 $/kWhe) over the entire optimisation horizon.
- **Optimistic scenario:** This scenario assumes conditions that would be favourable toward decarbonisation. As such, for electrolysers the lower limit of the provided cost range is used. In case of NG, higher cost will be advantageous towards decarbonisation. Thus, the "Low Economic Growth" scenario of Henry Hub projections is used, which forecasts higher future NG prices. Green electricity costs are considered to be 20% lower than those in the median scenario.
- **Pessimistic scenario:** This scenario, on the other hand, assumes conditions that would be unfavourable toward decarbonisation. As such, for electrolysers the upper limit of the provided cost range is used. In case of NG, lower cost will reinforce the current NG-based Grey Urea production techniques, thus discouraging its decarbonisation. Thus, the "High Oil and Gas Supply" scenario of Henry Hub projections is used, which forecasts lower future NG prices. Green electricity costs are considered to be 20% higher than those in the median scenario.

b). Plant-level analysis

The main objective of this analysis is to investigate the economic feasibility of different decarbonisation strategies, tailored for each existing Urea plant, by performing a plant-level cost analysis. This analysis assumes the same economic assumptions as the "median" scenario in the sectoral analysis describes above. However, in comparison to the sectoral analysis, this analysis also considers inflation in its cost analysis.

A Urea plant can achieve decarbonisation using several possible ways (called as Decarbonisation Scenarios hereafter), such as, by continuing its Grey Urea operation until retirement and then getting replaced by a Greenfield Green Urea plant, or by first getting retrofitted to a Brownfield Green Urea plant and then getting replaced by a Greenfield Green Urea plant upon retirement. Furthermore, since the Urea plants in India widely differ in their age (2 years to as high as 57 years), these decarbonisation strategies should be tailored based on a plant's retirement age. Thus, to be able to recommend plant-specific decarbonisation strategies, the following techno-economic modelling were undertaken:

(i). Greenfield plants

Future Urea plants can adopt Grey, Blue, or Green Urea production routes, each with varying costs due to technological differences. Additionally, the commissioning year will affect these costs because of factors like annual variations in natural gas prices and anticipated reductions in electrolyser costs due to technological advancements. Therefore, for Greenfield plants we estimate the LCOU for each production route for commissioning years between 2025 and 2050, with a project lifetime limited to 25 years. Given that 1.27 MMT/annum capacity is prevalent among recent Urea plant installations in India, with HURL Sindri being one of the most recently commissioned, this plant is considered as a benchmark for future Greenfield installations. Consequently, the operating parameters for modelling Greenfield plants are based on those of HURL Sindri[13].

This cost model serves not only as a reference for future, standalone Greenfield installations, but it is also used in the different scenarios for existing plants, wherever the option of retrofitting it with a Greenfield plant is considered.

(ii). Existing plants

India has a total of 36 Urea plants, with commissioning dates ranging from 1967 to 2022. This results in a wide range of retirement years (assuming a useful plant life of 60 years), necessitating individualised decarbonisation scenarios. To address this, existing Urea plants are grouped based on their age, and tailored decarbonisation strategies are developed for each group. The plants are categorized into five groups: "PG1" to "PG5". PG1 represents the oldest plants, set to retire in the near future (2025-2030), while PG5 represents the youngest plants, expected to retire after 2075.

These plant groups and their respective decarbonisation scenarios are outlined below. Any scenario that involves the continued operation of an existing plant as a Grey Urea plant will require periodic renovation and modernisation (R&M) to ensure efficient and uninterrupted operation. It is assumed that the plant's average operation and maintenance (O&M) costs observed over the past five years, adjusted for inflation, will be sufficient for its continued operation through R&M.

Plants retiring between 2025-2030 (PG1)

This group consists of the oldest of all Urea plants in the country. The four decarbonisation strategies considered for this group are:

1. Greenfield Grey after retirement
2. Greenfield Blue after retirement
3. Greenfield Green after retirement
4. Continue plant operation until 2050 with R&M

Since plants in this groups are soon reaching the end of their useful life, the first three of the four scenarios assume their continued operation (as Grey Urea plant) with the help of periodical R&M until plant's retirement, after which the plant is replaced with a Greenfield plant, based on either Grey, Blue or Green Urea production technique. The fourth strategy assumes a continued operation (as Grey Urea plant) with the help of periodical R&M, such that it can operate throughout the period of its LCOU calculation (2025-2050).

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[13] These details were obtained from a site visit conducted in May 2023.

Illustration: Gujarat State Fertilizers and Chemicals Ltd (GSFC), Vadodara

GSFC Vadodara will reach the age of 60 (and its assumed year of retirement) in 2027. Thus, the LCOU calculation in its case consists of:

- The O&M costs of the existing Grey plant from the start year of simulation to its retirement (i.e., 2025-2027), and,
- The investment, and O&M costs of the Greenfield plant operation over its assumed economic lifetime of 25 years (2028-2052), Thus, the total project lifetime of the calculated LCOU is 28 years (2025-2052). It should also be noted that if an existing plant is to be replaced by a Greenfield plant, the replacement capacity of 1.27 MMT/annum is considered, irrespective of the existing plant's production capacity.

Plants retiring between 2030-2040 (PG2)

The Urea plants in this group have up to 16 years of remaining plant operation (as of in 2024), allowing the consideration of intermediate decarbonisation strategies until their retirement. Their decarbonisation strategies are:

1. Greenfield Blue after retirement
2. Greenfield Green after retirement
3. Brownfield Blue in 2025 and then to a Greenfield Blue plant between 2030-2040
4. Brownfield Green in 2025 and then to a Greenfield Green plant between 2030-2040
5. Continue plant operation until 2050 with R&M

Illustration: IFFCO, Phulpur

The first two of the five scenarios assume a continued plant operation (as Grey Urea plant) with the help of periodical R&M until the plant's retirement, after which it is replaced with a Greenfield plant, based on either Blue or Green Urea production technique.

In case of IFFCO Phulpur, the assumed year of retirement is 2040, when it reaches the age of 60. Thus, the LCOU calculation in its case consists of:

- The O&M costs of the existing Grey plant from the start year of simulation to its retirement (i.e., 2025-2040), and,
- The investment and O&M costs of the Greenfield plant operation over its assumed economic lifetime of 25 years (2041-2065).

  Thus, the total project lifetime of the calculated LCOU is 41 years (2025-2065).

The latter two strategies consider the retrofitting this plant to employ Brownfield Blue/Green Urea production technique in 2025 and operating it until a certain year between 2030-2040. Then, a second retrofit is performed in the following year, to replace it with a Greenfield plant based on the Blue / Green Urea production technique. The optimal year of second retrofit is based on the lowest LCOU observed over the total project lifetime. In case of IFFCO Phulpur, the optimal year was found to be 2036. Thus, the LCOU calculation for IFFCO Phulpur in scenarios iii & iv consists of:

- First retrofit consisting of the investment, and O&M costs to Brownfield Blue/Green Urea plant from the start year of simulation to a year before optimal year (i.e., 2025-2035), and,

- Second retrofit consisting of the investment, and O&M costs to Greenfield Blue/Green Urea plant operation over its assumed economic lifetime of 25 years (2036-2060).

  Thus, the total project lifetime of the calculated LCOU is 36 years (2025-2060).

The fifth scenario assumes a continued plant operation (as Grey Urea plant) with the help of periodical R&M, such that it can operate throughout the period of its LCOU calculation (2025-2050).

Plants retiring between 2040-2050 (PG3)

The Urea plants in this group have up to 26 years of remaining plant operation (as of 2024). The decarbonisation scenarios modelled for them are:

1. Greenfield Blue after retirement
2. Greenfield Green after retirement
3. Brownfield Blue between 2025-2050 until retirement and then to a Greenfield Green plant
4. Brownfield Green between 2025-2050 until retirement and then to a Greenfield Green plant
5. Continue plant operation until 2050 with R&M

Illustration: Indo Gulf Fertilisers (IGF), Jagdishpur

The first two scenarios assume a continued plant operation (as Grey Urea plant) with the help of periodical R&M until the year of plant retirement, after which the plant is replaced with a Greenfield plant based on either Blue or Green Urea production technique. As IGF Jagdishpur will reach the age of 60 (and its assumed year of retirement) in 2048, its LCOU calculations in these two scenarios consists of:

- The O&M costs of the existing Grey plant from the start year of simulation to the year of retirement (i.e., 2025-2048), and,
- Retrofit consisting of the investment, and O&M costs of the Greenfield Blue/Green Urea plant operation over its assumed economic lifetime of 25 years (2049-2073). Thus, the total project lifetime of the calculated LCOU is 49 years (2025-2073).

The latter two strategies consider the continued plant operation (as Grey Urea plant) with the help of periodical R&M until a certain year between 2025 and 2050, then performing the (first) retrofit in the following year ("optimal year") to employ Brownfield Blue/Green Urea production technique and operating it for the next 25 years. We simulated every five-year period between 2025-2050 (2025, 2030, ..., 2050) to find the most cost optimal year to perform this retrofit. Then, a second retrofit is performed a year after plant's original retirement year to replace it with a Greenfield Green Urea plant. In the case of IGF Jagdishpur, the optimal year for the first retrofit was found to be 2035. Thus, the LCOU calculation in such a case consists of:

- The O&M costs of the Brownfield Grey plant from the start year of simulation to the year before the optimal year of first retrofit (i.e., 2025-2034),
- First retrofit consisting of the investment, and O&M costs of the Brownfield Blue/Green Urea plant operation to the year of retirement (i.e., 2035-2048), and,
- Second retrofit consisting of the investment, and operational and maintenance costs of the Greenfield Green Urea plant operation over its assumed economic lifetime of 25 years (2049-2073).

  Thus, the total project lifetime of the calculated LCOU is 49 years (2025-2073).

The fifth scenario assumes a continued plant operation (as Grey Urea plant) with the help of periodical R&M, such that it can operate throughout the period of its LCOU calculation (2025-2050).

Plants retiring between 2050-2060 (PG4)

These Urea plants in this group have up to 36 years of remaining plant operation (as of in 2024). Their decarbonisation scenarios are:

1. Greenfield Blue after retirement
2. Greenfield Green after retirement
3. Brownfield Blue between 2025-2050
4. Brownfield Green between 2025-2050
5. Continue plant operation until 2050

The first two of the five strategies assume a continued plant operation (as Brownfield Grey Urea plant) with the help of periodical R&M until the year of plant retirement, after which the plant is replaced with a Greenfield plant based on either Blue or Green Urea production technique.

Illustration: Yara Fertilisers India Pvt Ltd., Babrala

Yara will attain the age of 60 in 2054. Thus, the LCOU calculation in the first two scenarios consists of:

- The O&M costs of the Brownfield Grey plant from the start year of simulation to the year of retirement (i.e., 2025-2054), and
- Retrofit consisting of the investment, and O&M costs of the Greenfield Blue/ Green Urea plant operation over its assumed economic lifetime of 25 years (2055-2074[14]).

Thus, the total project lifetime of the calculated LCOU is 50 years (2025-2074).

The latter two scenarios assume a continued plant operation (as Brownfield Grey Urea plant) with the help of periodical R&M until a certain year, after which the plant is replaced (i.e., retrofitted) in the following (cost-optimal) year to operate on either Blue or Green Urea production technique. We simulated every five-year period between 2025-2050 to perform the retrofit (2025, 2030, ..., 2050) to arrive at the most cost optimal year. In case of Yara, the cost-optimal year is found to be 2035 (although in the graph, we also show the year 2025 for the purpose of comparison). Thus, the LCOU calculation in such a case consists of:

- The O&M costs of the Brownfield Grey plant from the start year of simulation to a year before optimal year (i.e., 2025-2034), and,
- Retrofit consisting of the investment, and O&M costs of the Brownfield Blue/ Green Urea plant operation over its assumed economic lifetime of 25 years (2035-2059). Thus, the total project lifetime of the calculated LCOU is 35 years (2025-2059).

The fifth strategy assumes a continued plant operation (as Brownfield Grey Urea plant) with the help of periodical R&M, such that it can operate throughout the period of its LCOU calculation (2025-2050).

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[14] Although an economic plant life of 25 years would entail an operational period of 2055-2079, all calculations are limited to the year 2074 due to limitated availability of input data

Plants retiring after 2075 (PG5)

This group consists of the newest Urea plants with at least 51 years of remaining plant operation (as of in 2024). Their decarbonisation strategies are:

1. Greenfield Blue after 25 years of plant operation
2. Greenfield Green after 25 years of plant operation
3. Brownfield Blue after 25 years of plant operation
4. Brownfield Green after 25 years of plant operation
5. Continue plant operation until 2050

Illustration: Chambal Fertilisers and Chemicals Limited (CFCL), Gadepan-III

The first two of the five strategies assume a continued plant operation (as Grey Urea plant) with the help of periodical R&M for a period of 25 years from the date of plant commissioning, after which the plant is replaced with a Greenfield plant based on either Blue or Green Urea production technique.

CFCL Gadepan-III was commissioned in the year 2019. Thus, the LCOU calculation in such a case consists of:

- The O&M costs of the existing Grey plant from the start year of simulation to the 25 years after plant commissioning (i.e., 2025-2043), and,
- Retrofit consisting of the investment, and O&M costs of the Greenfield Blue/ Green Urea plant operation over its assumed economic lifetime of 25 years (2044-2068).

Thus, the total project lifetime of the calculated LCOU is 44 years (2025-2068).

The latter two strategies are similar to the preceding two in terms of project lifetime and differ only in terms of installation type (Brownfield vs Greenfield).

The fifth strategy assumes a continued plant operation (as Brownfield Grey Urea plant) with the help of periodical R&M, such that it can operate throughout the period of its LCOU calculation (2025-2050).

It is to be noted, that while comparing the LCOUs of different decarbonisation scenarios for a given plant, the difference in their project lifetime should also be taken into consideration.

2. Remix Framework

The modelling was done using the Python programming language and the REMix framework ("Renewable Energy MIX for a sustainable energy supply"). REMix is an open-source framework developed at DLR, Germany[15], specifically designed for setting up optimisation models. Its primary purpose lies in conducting broad techno-economic assessments of possible future energy system designs and analysing interactions between various technologies using a high spatial and temporal resolution of the system.

For the purpose of this study, each Urea plant is modelled as a data node in REMix (with plant IDs i00, i01, …). The major processes or technologies have been

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[15] Gils, Hans Christian; Scholz, Yvonne; Pregger, Thomas; Luca de Tena, Diego; Heide, Dominik (2017): Integrated modelling of variable renewable energy-based power supply in Europe. In Energy 123, pp. 173–188. DOI: 10.1016/j.energy.2017.01.115

grouped within each plant node based on their primary function. They are known as converters within the REMix framework. For example, an NG-based Grey Urea plant will consist of these four converters: captive power plant (CPP), steam-methane reforming (SMR), Ammonia synthesis, and Urea synthesis.

Each of these converters facilitates conversion processes to transform one commodity into another. For instance, utilising the commodity NG, the CPP converter can generate commodities such as steam, electricity, and CO_2 emissions based on exogenously provided process efficiencies.

Designating the premises of the Urea plant as our system boundary, commodities entering this boundary are referred to as originating from a so-called source. For instance, the commodities natural gas or renewable electricity enter the system from their respective sources. Conversely, when a commodity exits the system, it is designated as going into a so-called sink. Examples include commodities like CO_2 or Urea that leave the system boundary and are described as going to their respective sinks. Defining these sources and sinks is crucial, as the flow of commodities from a source or into a sink generally involves associated monetary costs, along with allowing the possibility of limiting their flow. For instance, while accounting for a specific purchase price ($_nominal/MMBTu) in a given year, it is possible to restrict the amount of NG flowing into a node. This constraint could prompt the system to explore alternative options to meet Urea demand, such as transitioning to greener production technologies that would not rely upon the restricted commodity.

3. Calculating the Levelised Cost of Urea

The pivotal parameter guiding this transition is the cost of production, measured here as the LCOU, defined as the levelised cost of producing Urea ($\$_{2025}$/MT of Urea) over the project's lifetime (PL), discounted to the year 2025. The following steps are followed to calculate the LCOU:

1. Calculate the annualized capital investment ($C_{invest,y}$), which are inflated, using the equations (1) to (3). This exercise provides annual values (in $\$_{nominal}$/a) for each year (y) of the project lifetime for each technology (t) installed in the plant.

   Annualization of capital investment using equations (1) and (2):

$$c_{invest_{not\,inflated},y,t} = capital\_cost_t \cdot f_{annuity} \qquad \forall y,t \tag{1}$$

$$f_{annuity} = \frac{i \cdot (1+i)^{t_a}}{i \cdot (1+i)^{t_a} - 1} \tag{2}$$

$$c_{invest,y,t} = c_{invest_{not\,inflated},y,t} \cdot inflation_{cumsum,y} \qquad \forall y,t \tag{3}$$

   It should be noted that $C_{invest_{not\,inflated},y,t}$ is calculated separately for the equity and debt portion of the capital cost $capital\_cost_t$ using the respective period of loan or equity while calculating annuity $f_{annuity}$. In eq.(3), the cumulated inflation is calculated annually from the base year of inflation (2022) using a given annual inflation rate.

1. Calculate annual operational costs ($C_{operation,y,t}$), consisting of fixed and variable cost components. In the analysis for a given Urea plant, the fixed cost component related to its current installation ($C_{OMFix,urea\_plant}$) consists of employee salaries and welfare, maintenance and repair, depreciation and amortization, financing costs, freight and handling, and other expenses. This

data is obtained from the financial reports of the fertilizer plants. For any new technology installation (t) in the Urea plant such as electrolyser, ASU, etc., the annual operational cost is based on a percentual share of the technology's capital investment ($C_{OMFix,perc\_share,t}$), as commonly expressed in the literature. For all the future years, this cost has been inflated.

On the other hand, the variable cost components, consisting mostly of energy-related expenses such as those on the consumption of NG, green electricity, etc., are based on their projected future prices (further elaboration below in Data and assumption), and are thus, not inflated.

This exercise provides annual values (in $\$_{nominal}$/a) for each year of the project lifetime. The following equation summarises the fixed and variable operating costs of a (decarbonized) Urea plant.

$$c_{operation,y} = \left(c_{OMFix,urea\_plant} + \sum_{t}^{T} \left(capital\_cost_t \cdot c_{OMFix,perc\_share,t} \right) \right) \cdot inflation_{cumsum,y} + c_{fuel,y} + c_{GreenElec,y} + c_{DMWater,y} \qquad \forall y \tag{4}$$

2. Calculate the annual cost of Urea (COU) over the project lifetime (in $\$_{nominal}$/MT of Urea) by summing the costs calculated in steps 3) and 4) over all technologies in the plant (t→T) and divide them by the amount of Urea produced in the respective year ($P_{urea,y}$).

$$COU_{nom,y} = \frac{\sum_t^T c_{invest,y} + c_{operation,y}}{P_{urea,y}} \qquad \forall y \tag{5}$$

Where, y is a year within the project lifetime.

3. Discount the calculated COUs to 2025 using the discounting factor for their respective years, leading to discounted COUs ($/MT of Urea) for each year over the project lifetime.

$$COU_{2025,y} = COU_{nom,y} \cdot disc\_factor\_2025_y \qquad \forall y \tag{6}$$

$$disc\_factor\_2025_y = \frac{disc\_factor\_2025_{y-1}}{(1 + discount\_rate)} \qquad \forall y \tag{7}$$

It should be noted that the discount factor for the starting year of the project period (2025, in this project) is taken as 1.

4. Finally, sum the discounted COUs over the entire project lifetime and divide it by the sum of discounting factors over this period, leading to the LCOU ($\$_{2025}$/MT of Urea).

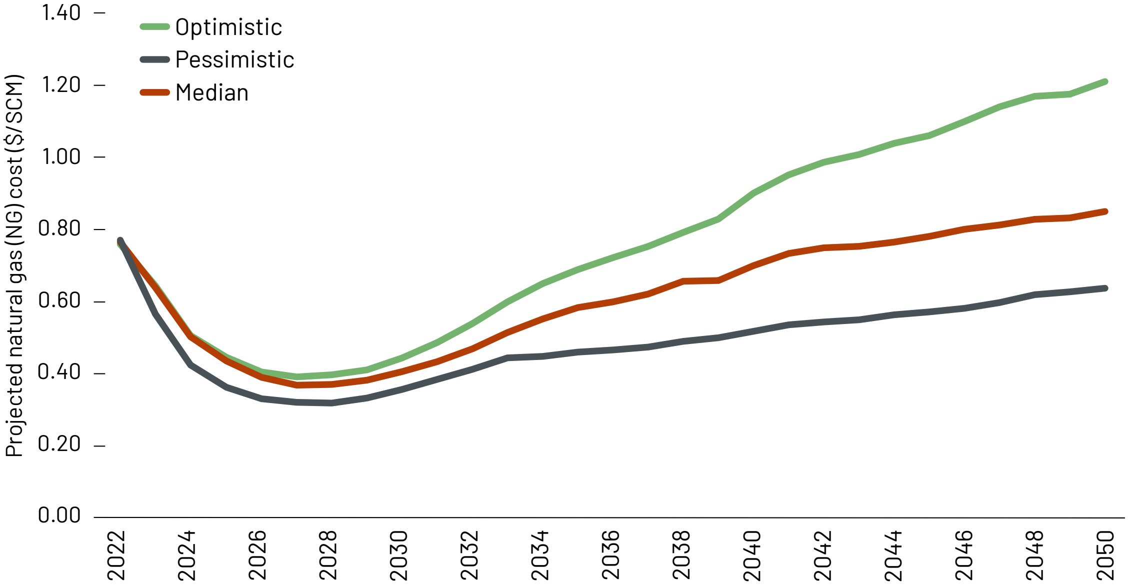
$$LCOU = \frac{\sum_y^Y COU_{2025}}{\sum_y^Y disc\_factor\_2025} \tag{8}$$

4. Data and Assumptions

(a). Grey Urea

To determine the levelised cost of Grey Urea, the critical factor is the future price of NG. This was forecasted based on the Henry Hub nominal price projections for natural gas in the USA from 2025 to 2050[16]. We correlated the Henry Hub Natural Gas prices in the USA with the prices of NG delivered to Urea plants in India from June 2015 to March 2023 at monthly intervals. This, in turn, allowed the development of a correlation factor which was then applied to the projected future Henry Hub nominal prices to estimate the NG prices for Urea plants in India till 2050. Post 2050, linear extrapolation of the trend up to that point was used to project prices. For the modelling of different scenarios discussed in the methodology, we use the reference case of US Henry Hub NG price projections to model the NG price in the "median" scenario. For the optimistic scenario, we utilize the "Low Economic Growth" scenario of Henry Hub prices, resulting in higher NG prices for the future. For the pessimistic scenarios, we utilize the "High Oil and Gas Supply" scenario of Henry Hub, resulting in lower NG price predictions. This data is shown in Graph 17.

Graph 1: Projected Prices of NG in India (Nominal)



Source: U.S. Energy Information Administration and iFOREST analysis

Other data and assumptions used for modelling the LCOU of Grey Urea is given in Table 1.

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[16] U.S. Energy Information Administration (EIA)(2023): Annual Energy Outlook 2023. Online verfügbar unter https://www.eia.gov/outlooks/aeo/data/browser/.

Table 1: Key Data and Assumptions for Grey Urea Deployments

Description	Unit	Value	Reference
a). Greenfield Plant			
Capacity	MMT	1.27	As per the capacity of 6 most recently commissioned Urea plants in India
Capital Cost	$/MT	800-850	As observed in HURL Sindri, installed in November 2022, which is the latest installed plant in India.[17]
O&M Cost	% of capital cost	9	As per financial data of sample new plants. The average value was considered.
Energy consumption	Gcal/MT Urea	5.3	HURL Sindri
It is assumed that the Greenfield plants will be set-up on the existing sites, using existing infrastructure.			
b). Brownfield Plant			
Retirement age	Years	60	As per Box 3
O&M cost	$/MT	Average of last 4 years	Calculated for each plant based on Annual report
Cost of Natural Gas	$/MMBTU	Graph 4	Projected based on Henry Hub nominal price
Profit before tax	% of turnover	Average of last 4 years	Calculated for each plant based on Annual report
Energy consumption	Gcal/MT Urea	Average of last 4 years	Calculated for each plant based on data reported to Department of Fertiliser and Fertiliser Association of India.
It is assumed that the performance of the existing Grey Urea plants will be maintained till retirement with the help of R&M			

(b). Green Urea

For modelling the levelised cost of Green Urea, the following technological options have been chosen:

- Alkaline Electrolyser for H_2 production
- Cryogenic distillation for N_2 production
- Chemical Solvent Absorption for Carbon capture. Further, it has been assumed that CO_2 for each plant will be sourced from nearby emitting industries (within a radius of 150 km) through a pipeline.

Annexures 1, 2 and 3 provide detailed reasons for making these technological choices.

The data and assumptions used for modelling the LCOU of Green Urea are given in Table 2.

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[17] Department of Fertilizers, MoCF (December, 2022), Rajya Sabha question no 139, Answered on 20.12.2022. Government of India. https://sansad.in/getFile/annex/258/AS139.pdf?source=pqars

Table 2: Key Data and Assumptions for Green Urea Deployments

Description	Unit	Value		Reference
Cost-range for Alkaline electrolyser	$/kW	Year	Cost	The Future of Hydrogen - Seizing today's opportunities[18]
		2020	500-1400	
		2030	400-850	
		2040	200-700	
Electrolyser efficiency	%	Year	Efficiency	The Future of Hydrogen - Seizing today's opportunities[19]
		2020-2030	66	
		2030-2040	68	
		2040-2050	75	
Lower heating value of hydrogen	MJ/kg	119.96		NIST Standard Reference Database Number 69[20]
Energy consumption	Gcal/MT Urea	5.4		iFOREST analysis
O&M cost of electrolyser	% of capital cost	7% for 2020 – 2030 and 5% thereafter. Additional costs of periodic replacement of components such as electrolyser stacks have been considered in this expenditure.		A Green Hydrogen Economy for India: Policy and Technology Imperatives to Lower Production Cost[21]
Cost of Demineralised water	$/ MT	1.25		A Green Hydrogen Economy for India: Policy and Technology Imperatives to Lower Production Cost[22]
Cost of Green electricity	$/kWh	Year	Cost	Considered previously finalised Round The Clock (RTC) RE supply contracts. These were averaged and a premium was added[23]. Cost reductions of 2.5 – 2.0 percent annually are expected.
		2025–2030	0.0575	
		2030–2035	0.05	
		2035–2040	0.045	
		2040-2050	0.04	
ASU Capex	$/ MT N_2/h	15,00,000		Power-to-ammonia in future North European 100 % renewable power and heat system[24]

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[18] Anon. 2019. The Future of Hydrogen - Seizing today's opportunities. International Energy Agency. Pg- 45 https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

[19] ibid

[20] Linstrom. P. (2021). NIST Chemistry WebBook. NIST Standard Reference Database Number 69. NIST Office of Data and Informatics. doi:10.18434/T4D303.

[21] Biswas. T., Yadav. D., Baskar. A. (December, 2020), A Green Hydrogen Economy for India: Policy and Technology Imperatives to Lower Production Cost, India, Council on Energy, Environment and Water. https://www.ceew.in/sites/default/files/CEEW-A-Green-Hydrogen-Economy-for-India-14Dec20.pdf

[22] ibid

[23] https://solarquarter.com/2023/04/10/indian-railways-awards-1-gw-rtc-hybrid-power-auction-to-sprng-energy-ntpc-ayana-power-and-o2-power/, https://cleantechnica.com/2020/02/01/india-allocates-1-2-gigawatts-in-worlds-largest-renewable-energy-storage-tender/ and https://www.mercomindia.com/seci-retender-rtc-renewables-bundled-thermal

[24] Ikäheimo, J.; Kiviluoma, J.; Weiss, R.; Holttinen, H. (2018), Power-to-ammonia in future North European 100 % renewable power and heat system. International Journal of Hydrogen Energy 2018, 43, 17295–17308 Power-to-ammonia in future North European 100 % renewable power and heat system - ScienceDirect

Table 2 continued

Description	Unit	Value		Reference
O&M cost of ASU	% of capital cost	2		Power-to-ammonia in future North European 100 % renewable power and heat system[25]
Power consumption of ASU	kWh/ MT N_2	265		Power-to-ammonia in future North European 100 % renewable power and heat system[26]
Carbon capture				
Levelised cost of CO_2 production	\$/ MT CO_2	Year	Cost	Carbon Capture Utilisation and Storage (CCUS) – Policy Framework and Deployment Mechanism in India[27]
		2023	40	
		2050	30	
Cost of transporting carbon dioxide	\$/ MT CO_2 in 2024	\$7 for 100 km \$10 for 150 km		iFOREST Analysis
Cost of Electric Steam generator	Million \$/ MW	0.13		Long-term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU[28]
Switch yard capital cost	Million \$	33.9		Cost taken from supplier of the package

(c). Blue Urea

The key data and assumptions used for modelling Blue Urea is given in Table 3. The other costs and assumptions used in Blue Urea are similar to those of Grey and Green Urea.

Table 3: Key Data and Assumptions for Blue Urea Deployments

Description	Unit	Value	Reference
Percentage of green hydrogen blending	% of ammonia equivalent	40	iFOREST analysis
Percentage reduction in natural gas	%	30	iFOREST analysis
Energy consumption	Gcal/MT Urea	5.8	iFOREST analysis

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25 ibid

26 ibid

27 Anon. (2022) Carbon Capture Utilisation and Storage (CCUS) – Policy Framework and Deployment Mechanism in India P-139, NITI Aayoga https://www.niti.gov.in/sites/default/files/2022-12/CCUS-Report.pdf

28 European Commission, Long-term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU, pg – 32 of 186. https://publications.jrc.ec.europa.eu/repository/handle/JRC109006

(d). Financial parameters

The financial parameters used for modelling LCOU is given in Table 4.

Table 4: Financial Parameters for Modelling

Description	Unit	Value	Reference
Inflation rate on plant and machinery	%	3	Weighted average inflation rate for the last 10 years (2013 – 2022) in wholesale price index for manufacturing of the selected commodities related to Urea plant[29].
Inflation on O&M	%	4	Weighted average of: 1. Labour cost inflated by 10 year average of CPI[30] (5.95%). 2. Other O&M cost (6% of CAPEX) inflated by 10 year average WPI[31] on selected commodities.
Debt equity ratio	-	70:30	Financial Risk Assessment of Public Private Partnership Project, India[32].
Return on equity	%	12	Industry standard
Interest on loan	%	10	Industry standard
Period of Depreciation	Years	25	Company Act 2013[33]
Operational days in a year	Days	330	Design of a plant for the production of ammonia and Urea using aspen HYSYS[34].
Discount Rate	%	8.3	CERC RE Tariff Order for Fy 2021-22[35].
Loan Period	Years	13	Industry standard
All constant parameters (such as Return on Equity, Loan Period etc.) have been estimated as per prevailing market trends.			

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[29] Office of the Economic Adviser, Department For Promotion Of Industry And Internal Trade, Ministry Of Commerce & Industry, 2023, Annual Average of Monthly Index (Calender Year 2013 Onwards), Government of India https://eaindustry.nic.in/download_data_1112.asp

[30] Inflation rates in India, https://www.worlddata.info/asia/india/inflation-rates.php

[31] Office of the Economic Adviser, Department For Promotion Of Industry And Internal Trade, Ministry Of Commerce & Industry, 2023, Annual Average of Monthly Index (Calender Year 2013 Onwards), Government of India https://eaindustry.nic.in/download_data_1112.asp

[32] Singh. A., Shrivastava. P., Kambekar. A., (2019), Financial Risk Assessment of Public Private Partnership Project, India, Proceedings of Sustainable Infrastructure Development & Management (SIDM) 2019, pg 7 of 10. Available at SSRN: https://ssrn.com/abstract=3369415 or http://dx.doi.org/10.2139/ssrn.3369415

[33] Ministry of Company Affairs, (2013), Company Act 2013, Government of India. Pg – 255 https://www.mca.gov.in/Ministry/pdf/CompaniesAct2013.pdf

[34] Nweke. J. et. al. (2021). Design of a plant for the production of ammonia and Urea using aspen HYSYS. Volume 10, Issue 6, June 2022. Nigeria, Global Scientific Journals. https://www.researchgate.net/publication/362861841_Design_of_a_plant_for_the_production_of_ammonia_and_Urea_using_aspen_HYSYS

[35] Central Electricity Regulatory Commission, 2021, CERC RE Tariff Order for Fy 2021-22, Government of India. https://cercind.gov.in/2021/orders/2-SM-2021.pdf

References

Chapter 1: India's Use of Fertilisers and Urea

1. Mancombu. S., (August 15, 2022), How India overcame food emergency, attained self-sufficiency, The Hindu Businessline.
2. The Fertiliser Association of India (2022), All-India Consumption of Fertiliser Nutrients - 1950-51 to 2021-22 https://www.faidelhi.org/general/con-npk.pdf
3. The Fertiliser Association of India (2023), Annual review of fertilizer production and consumption 2022-23 https://www.faidelhi.org/general/AR-Ex-Sum.pdf
4. Fertiliser Statistics 2021-22 (2022), 67th edition, Fertiliser Association of India, Delhi, pg. I-96 https://fertiliserindia.com/wp-content/uploads/2023/05/Fertiliser-Stat-Book-2021-22.pdf
5. The Fertiliser Association of India (2023), Annual review of fertilizer production and consumption 2022-23 https://www.faidelhi.org/general/AR-Ex-Sum.pdf
6. Agricultural Statistics at a Glance 2022, Department of Agriculture & Farmers Welfare, Economics & Statistics Division, Ministry of Agriculture & Farmers Welfare, GOI
7. Ministry of Agriculture and farmers welfare, (October 18, 2023), Delhi. https://pib.gov.in/PressReleasePage.aspx?PRID=1968931#:~:text=As%20per%20Final%20Estimates%20for,tonnes%20achieved%20during%202021%2D22.
8. TFI. (2016, October 31). Fertilizer 101: The big 3 - nitrogen, phosphorus and potassium. The Fertiliser Institute. https://www.tfi.org/the-feed/fertilizer-101-big-3-nitrogen-phosphorus-and-potassium
9. Khurana, A., & Kumar, F. (2022). State of Biofertilizers and Organic Fertilizers in India. Centre for Science and Environment. https://www.cseindia.org/state-of-biofertilizers-and-organic-fertilizers-in-india-11235
10. The Fertiliser Association of India (2023), Annual review of fertilizer production and consumption 2022-23 https://www.faidelhi.org/general/AR-Ex-Sum.pdf
11. ibid
12. Anon, (April, 2023), Fertiliser Production, Import & Sales in India during FY' 2022-23 till March https://fertiliserindia.com/fertiliser-production-import-sales-in-india-during-fy-2022-23-till-march/
13. Anon (2022), Fertilizer Industry Handbook, India, Yara, pg-46 https://www.yara.com/contentassets/29b0f7802aae4f7face19d5c3495be77/fertilizer-industry-handbook-2022.pdf/
14. The Fertiliser Association of India (2023), Annual review of fertilizer production and consumption 2022-23 https://www.faidelhi.org/general/AR-Ex-Sum.pdf
15. Anon (2022), Fertilizer Industry Handbook, India, Yara, pg-46 https://www.yara.com/contentassets/29b0f7802aae4f7face19d5c3495be77/fertilizer-industry-handbook-2022.pdf/
16. Jigeesh, A. M. (2023, July 11). "Our Attempt is to end Import Dependency on Urea by 2025 and Replace it with Nano Urea and other Alternate Forms of Urea." The Hindu. https://www.thehindu.com/news/national/our-attempt-is-to-endimport-dependency-on-Urea-by-2025-and-replace-it-with-nano-Urea-and-other-alternate-forms-of Urea/article67064913.ece
17. Annual Report 2022-23, Ministry of Petroleum and Natural Gas https://mopng.gov.in/files/TableManagements/annualreport2223.pdf
18. National Statistical Office, Ministry Of Statistics and Programme Implementation (January, 2022), Energy Statics India 2022, Government of India. Accessed here

19. Fertiliser India. (2023, April 28). India's expenditure on fertiliser subsidies during the FY'2022-23 (April 2022 to March 2023) India's expenditure on fertiliser subsidies during the FY'2022-23 (April 2022 to March 2023) -. https://fertiliserindia.com/indias-expenditure-on-fertiliser-subsidies-during-the-fy2022-23-april-2022-to-march-2023/
20. Finance Department Government of Assam. (n.d.). Highlights of Budget 2023-24. https://www.cbgaindia.org/wp-content/uploads/2023/03/Budget-Highlights-2.pdf
21. Bhushan, C. et al. (2019), GRAIN BY GRAIN, Green rating of the fertilizer sector, Delhi, Centre for Science and Environment. https://csestore.cse.org.in/usd/grain-by-grain-green-rating-of-the-fertilizer-sector.html
22. The Fertiliser Association of India (2023), Annual review of fertilizer production and consumption 2022-23 https://www.faidelhi.org/general/AR-Ex-Sum.pdf
23. Brentrup, F., & Palliere, C (n.d.). Nitrogen use efficiency as an AGRO- environmental indicator - OECD. OECD.org. https://www.oecd.org/greengrowth/sustainable-agriculture/44810433.pdf
24. iFOREST Analysis
25. Anon. (2016). Global warming potential values. Greenhouse gas Protocol. https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values (Feb 16 2016)_1.pdf
26. Anon. (n.d.-b). World Emissions Clock. https://worldemissions.io/

Chapter 2: India's use of Fertilisers and Urea

1. Fertiliser Statics Book 2021-22 (2022), 67th edition, Fertiliser Association of India, Delhi, pg. I-48. https://fertiliserindia.com/wp-content/uploads/2023/05/Fertiliser-Stat-Book-2021-22.pdf
2. Anon, (April, 2023), Fertiliser Production, Import & Sales in India during FY' 2022-23 till March. https://fertiliserindia.com/fertiliser-production-import-sales-in-india-during-fy-2022-23-till-march/
3. Anon (2022), Fertilizer Industry Handbook, India, Yara, pg-46 https://www.yara.com/contentassets/29b0f7802aae4f7face19d5c3495be77/fertilizer-industry-handbook-2022.pdf/
4. Pate, J. S., & Layzell, D. B. (2022, December). Carbon and nitrogen partitioning in the whole plant - a thesis based on empirical modeling. SpringerLink. https://link.springer.com/chapter/10.1007/978-94-009-8267-3_4#:~:text=Dry%20matter%20of%20plants%20contains,from%20which%20it%20is%20derived.
5. Anon. (2023, June 14). Top ten states of India's Urea PoS Sales : Command 82% of India's Urea market, marking significant growth in FY'2022-23. Top Ten States of India's Urea PoS Sales : Command 82% of India's Urea Market, Marking Significant Growth in FY'2022-23 -. https://fertiliserindia.com/top-ten-states-of-indias-Urea-pos-sales-command-82-of-indias-Urea-market-marking-significant-growth-in-fy2022-23/
6. Fertiliser Statics Book 2021-22 (2022), 67th edition, Fertiliser Association of India, Delhi. https://fertiliserindia.com/wp-content/uploads/2023/05/Fertiliser-Stat-Book-2021-22.pdf
7. Bhushan, C. et al. (2019), GRAIN BY GRAIN, Green rating of the fertilizer sector, Delhi, Centre for Science and Environment pg- 17. https://csestore.cse.org.in/usd/grain-by-grain-green-rating-of-the-fertilizer-sector.html
8. Agriculture Census Division, Department of Agriculture, Cooperation & Farmers Welfare (2021), All India report on Input Survey 2016-17, Ministry of Agriculture & Farmers Welfare, Government of India. https://agcensus.nic.in/document/is2016/air_is_16-17_210121-final_220221.pdf
9. Department of Agriculture, Cooperation & Farmers Welfare Directorate of Economics and Statistics, (2018), Agricultural Statistics at a Glance 2018, Ministry of Agriculture & Farmers Welfare, Government of India. https://eands.dacnet.nic.in/PDF/Agricultural%20Statistics%20at%20a%20Glance%202018.pdf
10. iFOREST analysis
11. Anon 2011. Carbon Footprint Reference Values, Fertilisers Europe, Brussels https://www.agindustries.org.uk/static/2a6d34b7-bcf9-4ac1-a2843dede9fde0d5/Mineral-Fertiliser-CarbonFootprint-Reference-Values-2011.pdf

12. Singh, V. (2022, August 5). Nitrogen use efficiency in crop production in India: Trends, issues, and Challenges - Agricultural Research. SpringerLink. https://link.springer.com/article/10.1007/s40003-022-00626-7
13. Dash D.K. (2023, January 9). Size matters: Small Urea bags help cut down consumption. The Times of India. https://timesofindia.indiatimes.com/india/reducing-Urea-bag-size-has-brought-down-fertilizer-consumption-report/articleshow/96836756.cms?from=mdr
14. Anon. (2014). National Mission for Sustainable Agriculture (NMSA) Operational Guidelines. NMSA. https://nmsa.dac.gov.in/pdfdoc/NMSA_Guidelines_English.pdf
15. Kumar. R., (2022), Organic farming status in India: A review, Punjab: The Pharma Journal. https://www.thepharmajournal.com/archives/2022/vol11issue12/PartAK/11-12-433-605.pdf
16. Gupta, N., Pradhan. S., Jain. A., and Patel. N. (2021). Sustainable Agriculture in India 2021: What We Know and How to Scale Up. New Delhi: Council on Energy, Environment and Water https://www.ceew.in/publications/sustainable-agriculture-india/organic-farming#:~:text=Paramparagat%20Krishi%20Vikas%20Yojana%20(PKVY)%20is%20a%20centrally%20sponsored%20scheme,Guarantee%20System%20(PGS)%20certification
17. Gowda, S. (2020, September 15). Government is encouraging urban local bodies (ULBs) to manage municipal solid waste in scientific manner including processing waste to-compost and other process. Press Information BUreau. https://pib.gov.in/PressReleasePage.aspx?PRID=1654529#:~:text=Govt%20has%20introduced%20a%20Policy,form%20of%20subsidy%20%3A%20Shri%20Gowda&text=The%20Government%20is%20encouraging%20Urban,to%2Dcompost%20and%20other%20process.
18. Gupta, N., Pradhan. S., Jain. A., and Patel. N. (2021). Sustainable Agriculture in India 2021: What We Know and How to Scale Up. New Delhi: Council on Energy, Environment and Water https://www.ceew.in/publications/sustainable-agriculture-india/organic-farming#:~:text=Paramparagat%20Krishi%20Vikas%20Yojana%20(PKVY)%20is%20a%20centrally%20sponsored%20scheme,Guarantee%20System%20(PGS)%20certification
19. Ibid
20. Ibid
21. Anon. (2018). Introduction of 45 kg bag of Urea. Department of Fertiliser . https://www.fert.nic.in/sites/default/files/What-is-new/Introduction of 45 kg bag of Urea.pdf
22. Rao. I. Sing, (2018, January 2) Using 45 kg bags may bring down Urea consumption, Governance Now.
23. Anon. (n.d.). National Bank for Agriculture and Rural Development. NABARD. https://www.nabard.org/content1.aspx?id=2791&catid=23&mid=23
24. Shagun. (2024). Dip in yield, low protein content: Pau Field Experiment finds several problems with Nano Urea. Down To Earth. https://www.downtoearth.org.in/news/agriculture/dip-in-yield-low-protein-content-pau-field-experiment-finds-several-problems-with-nano-Urea-93668
25. Rao. I. Sing, (2018, January 2) Using 45 kg bags may bring down Urea consumption, Governance Now.
26. Kumar. R., (2022), Organic farming status in India: A review, Punjab: The Pharma Journal. https://www.thepharmajournal.com/archives/2022/vol11issue12/PartAK/11-12-433-605.pdf
27. Ibid
28. Anon. Natural Farming, Andhra Pradesh, Niti Aayog. https://naturalfarming.niti.gov.in/andhra-pradesh/
29. Ibid
30. Ibid and Saldanha. L., (October 2018), A Review of Andhra Pradesh's Climate Resilient Zero Budget Natural Farming, India: Environment Support Group, http://esgindia.org/sites/default/files/education/community-outreach/press/crzbnf-review-saldanha-esg-oct-2018.pdf

31. Samstha. R., (2021), Andhra Pradesh Community managed Natural Farming (APCNF) Package of Practices https://drive.google.com/file/d/1MLLZvKBZY4uL4Pjfcc8r6pHWOryKLpNn/view https://apcnf.in/package-of-practices/
32. Ibid
33. Ibid

Chapter 3: Demand-Side Management

1. IFASTAT. (updated 2024). Global Nutrient Budget Database. IFA. https://www.ifastat.org/consumption/nutrient-use-efficiency
2. Silva. J. V., (2021), Agronomic analysis of nitrogen performance indicators in intensive arable cropping systems: An appraisal of big data from commercial farms, Field Crops Research, Volume 269, 108176, ISSN 0378-4290, https://doi.org/10.1016/j.fcr.2021.108176.
3. Ibid.
4. FAO (2018). The Future of Food and Agriculture: Alternative pathways to 2050. UN. https://www.fao.org/3/I8429EN/i8429en.pdf
5. Ibid.
6. FAO (2018). The Future of Food and Agriculture: Alternative pathways to 2050. UN. https://www.fao.org/3/I8429EN/i8429en.pdf
7. Ibid.
8. Bhushan, C. et al. (2019), GRAIN BY GRAIN, Green rating of the fertiliser sector, Delhi, Centre for Science and Environment. https://csestore.cse.org.in/usd/grain-by-grain-green-rating-of-the-fertilizer-sector.html
9. Sandhu. H., (2023), "Natural Farming Through a Wide-Angle Lens: True Cost Accounting Study of Community Managed Natural Farming in Andhra Pradesh, India." India and Switzerland: GIST Impact https://futureoffood.org/wp-content/uploads/2023/07/apcnf-tca-study_2023.pdf
10. Gupta, N., Pradhan. S., Jain. A., and Patel. N. (2021). Sustainable Agriculture in India 2021: What We Know and How to Scale Up. New Delhi: Council on Energy, Environment and Water https://www.ceew.in/publications/sustainable-agriculture-india/organic-farming#:~:text=Paramparagat%20Krishi%20Vikas%20Yojana%20(PKVY)%20is%20a%20centrally%20sponsored%20scheme,Guarantee%20System%20(PGS)%20certification.
11. Samba, R. (2022, January 1). The Potential Impact of Climate Change on the Micronutrient-Rich Food Suppl. Science Direct. https://doi.org/10.1093/advances/nmab104
12. Anon. Vision 2050, New Delhi, Indian Council of Agriculture Research. https://www.iari.res.in/files/vision/vision-2050.pdf
13. TOMAR, N. S. (2022, FEBRUARY 8). PROMOTION OF ORGANIC FARMING. PRESS INFORMATION BUREAU. HTTPS://PIB.GOV.IN/PRESSRELEASEPAGE.ASPX?PRID=1796561
14. Singh. B., (2022), Nitrogen Use Efficiency in Crop Production in India: Trends, Issues, and Challenges, https://doi.org/10.1007/s40003-022-00626-7. Springer link. https://link.springer.com/article/10.1007/s40003-022-00626-7
15. Silva. J. V., (2021), Agronomic analysis of nitrogen performance indicators in intensive arable cropping systems: An appraisal of big data from commercial farms, Field Crops Research, Volume 269, 108176, ISSN 0378-4290, https://doi.org/10.1016/j.fcr.2021.108176.

Chapter 4: Supply-Side Decarbonisation

1. iFOREST Analysis
2. Bhushan, C. et al. (2019), GRAIN BY GRAIN, Green rating of the fertiliser sector, Delhi, Centre for Science and Environment. https://csestore.cse.org.in/usd/grain-by-grain-green-rating-of-the-fertilizer-sector.html

3. iFOREST Analysis
4. iFOREST Analysis
5. iFOREST Analysis
6. India has 36 plants. But two plants — Brahmaputra Valley Fertilizer Corporation Limited: Namrup-II and III — were excluded as they were not operational or partially operational during the study period
7. These details were obtained from a site visit conducted in May 2023.
8. Chandra Bhushan, Sanjeev Kumar Kanchan, Sugandha Arora, Vinay Trivedi, Shobhit Srivastava, Kapil Subramanian and Shreya Verma 2019, Grain by Grain: Green rating of the fertilizer sector, Centre for Science and Environment, New Delhi

Chapter 5: Low Carbon Pathway for Urea Production and Consumption

1. The LCOU for the Green Urea Scenario is $475/MT.
2. The model has assumed a constant export price of $450 per MT Urea.
3. Christoph Bertram, Ottmar Edenhofer, and Gunnar Luderer, 2021, A path to Zero, Finance & Development Magazine, International Monetary Fund.
4. Yash P. Abrol et.al. (Eds), The Indian Nitrogen Assessment: Sources of Reactive Nitrogen, Environmental and Climate Effects, and Management Options and Policies, 2017, Elsevier.
5. https://mnre.gov.in/national-green-hydrogen-mission/
6. iFOREST estimates
7. Annual review of fertilizer production and consumption 2022-23, Fertilizer Association of India, New Delhi
8. https://pib.gov.in/newsite/PrintRelease.aspx?relid=114860

Notes

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https://iforest.global