Evaluating Net-zero for the Indian Fertiliser Industry

Marginal Abatement Cost Curves of Carbon Mitigation Technologies

Rishabh Patidar, Kartheek Nitturu, Deepak Yadav, and Hemant Mallya

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We estimate that the Indian fertiliser sector emits ~0.58 tonnes of CO_2 per tonne of fertiliser produced. The sector has a total emissions footprint of ~25 million tCO_2 for the year 2022-23.

Image: iStock

Executive summary

India is the second-largest fertiliser producer in the world, accounting for ~20 per cent of global production (Fertilizer Association of India 2023). Fertilisers, although essential for improving crop yield (Singh, et al. 2019), are significant source of greenhouse gas emissions due to energy-intensive production processes and extensive fossil fuel use, particularly natural gas. The Indian fertiliser industry contributes ~25 million tonnes of CO2 annually, which is ~1 per cent of India's total greenhouse gas emissions of ~3 giga tonnes (GHG platform India n.d.). Decarbonising the fertiliser sector can have two significant benefits: first, it can reduce fossil fuel use, which is essential to achieving net-zero targets. Second, it can result in significant import savings of approximately ~USD 10 billion, since ~60 per cent of the natural gas consumed in this sector is imported (Jain 2022). Therefore, in this study, we aim to provide options for the fertiliser industry to decarbonise and strategically achieve its net-zero targets.

A. Key insights

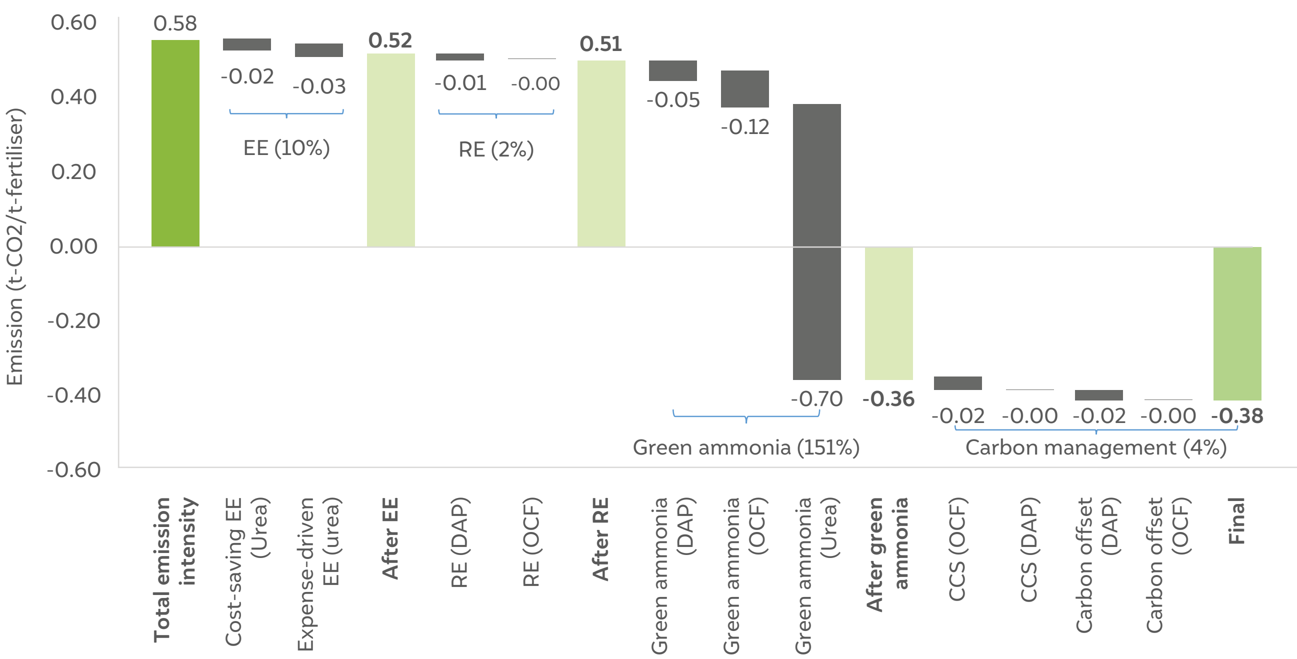
The Indian fertiliser industry emits 0.58 tonnes of CO_2 per tonne of fertiliser

We estimate that the Indian fertiliser sector emits ~0.58 tCO2 per tonne of fertiliser produced. The sector has a total emissions footprint of ~25 million tonnes of CO2 (MtCO2). While 85 per cent of the emission is attributed to the use of natural gas, which is used as a fuel and feedstock in the production process, the remaining 15 per cent is from electricity use. Urea production accounts for about 65 per cent of the total emissions from the sector, and the remaining is from the production of di-ammonium phosphate (DAP) and other complex fertilisers (OCF).

Green ammonia can make the Indian fertiliser industry net carbon-negative

Deploying energy efficiency (EE) measures can reduce the fertiliser industry's emissions intensity by ~10 per cent – from 0.58 t-CO_2/t-fertiliser to 0.52 t-CO_2/t-fertiliser (Figure ES1 shows the consolidated emissions mitigation trajectory of the Indian fertiliser industry). Because fertiliser production does not require much electricity, switching to renewable power would result in a mere 2 per cent reduction in emissions. Since ammonia production[1] accounts for ~95 per cent of the emissions in this sector, switching from grey to green ammonia[2] can result in a 151 per cent emissions reduction, thus resulting in net-negative emissions for the sector. The negative emissions can be attributed to the need to source CO_2 from

Figure ES1 Emission mitigation pathways for the fertiliser industry



Source: Authors' analysis

1 Ammonia is the main raw material for urea and other fertiliser products such as DAP and OCF.

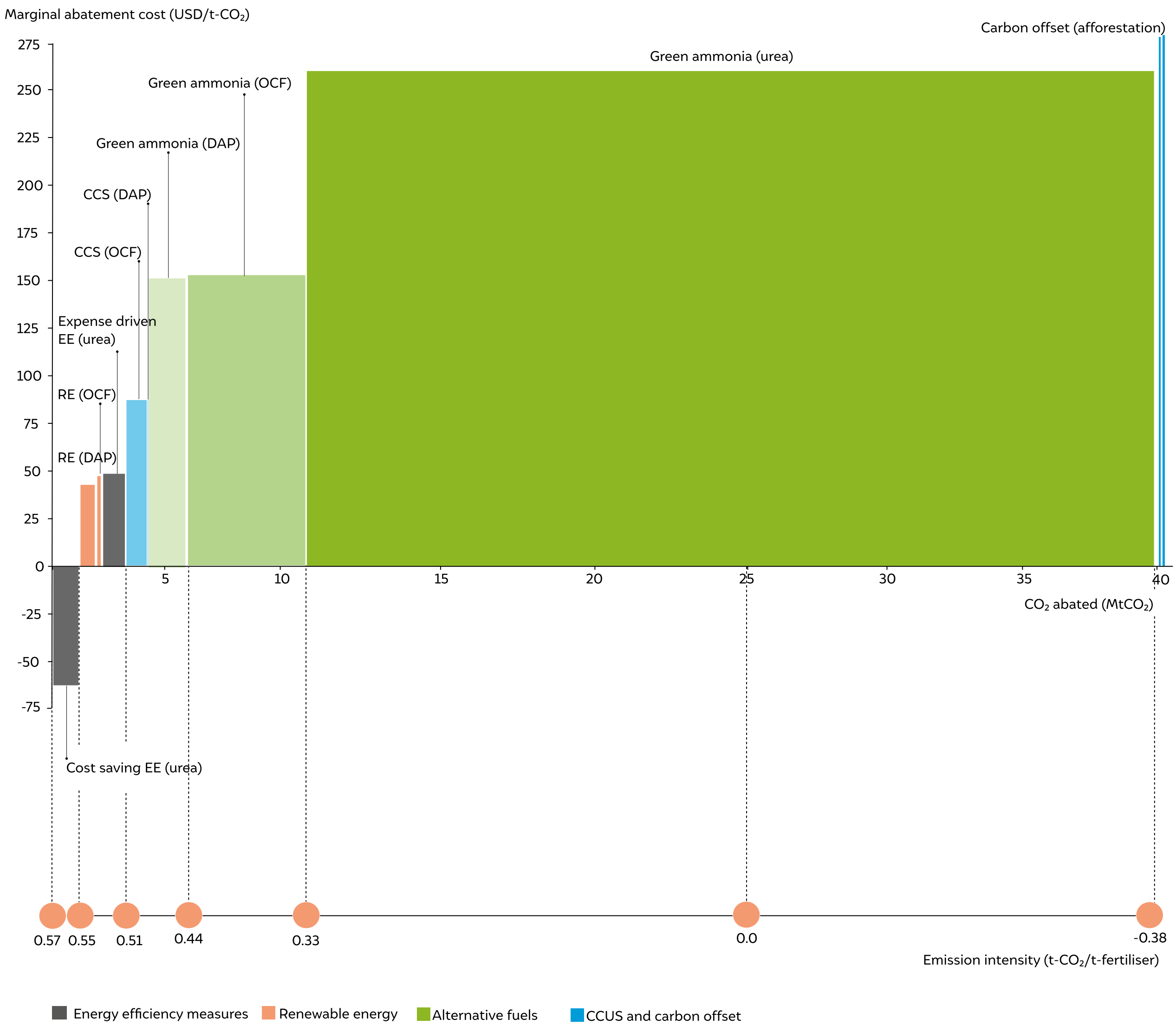
2 Grey ammonia is produced from fossil-based sources, while green ammonia is produced using renewable energy sources.

other emitters to produce urea. According to our estimate, the Indian fertiliser sector can consume ~20 MTPA of green ammonia. As a last resort, carbon management options such as carbon capture and sequestration (CCS), carbon capture and utilisation (CCU), and afforestation may be adopted.

Figure ES2 illustrates the marginal abatement cost (MAC) curve for the fertiliser industry. It shows that cost-saving EE technologies have the lowest mitigation cost of USD -63.5 per tonne. It is also the only cost-saving option in the MAC curve. However, expense-driven EE technologies have a MAC cost of USD 49.6 per tonne. Yet, taken together, EE technologies can help abate ~2.3 MtCO2. Renewable energy (RE) is the next mitigation option worth considering, with a MAC of ~USD 42 per tonne, especially for DAP and OCF production. However, since it can abate only 0.4 MtCO2, it is unlikely to play a significant role in decarbonising the fertiliser industry.

With a MAC of ~USD 160 per tonne for DAP and OCF each and ~USD 270 per tonne for urea, green ammonia can abate 2 $MtCO_2$ from DAP, 5.1 $MtCO_2$ from OCF, and 30 $MtCO_2$ from urea production. The MAC for the use of green ammonia in urea production is higher than those for DAP and OCF because the urea industry receives subsidised domestic gas priced at USD 7.5 per MMBtu, and we assume that imported natural gas priced at USD 10.1 per MMBtu is used for DAP and OCF production. The total emissions abated by using green ammonia alone in the urea sector stands at 30 $MtCO_2$, which is more than the current level of total emissions from the urea sector, which stands at 16.2 $MtCO_2$, as urea production needs CO_2, which has to be sourced from other sectors, making the fertiliser industry a net-negative industry.

Figure ES2 Cumulative MAC for the fertiliser sector



Source: Authors' analysis

With the implementation of carbon management measures, the MAC of CCS for DAP and OCF is estimated to be USD 90 per tonne, which has very limited potential to abate 0.006 and 0.1 $MtCO_2$ for DAP and OCF, respectively. Urea plants do not need any CCS, as the entire CO_2 abatement can happen with EE and green ammonia. It should be noted that while CCS has a lower abatement cost than green ammonia, the MAC curve reflects emissions mitigation through the use of green ammonia primarily because the cost of green ammonia is expected to decrease in the future and support India's ambitions of becoming *Aatma Nirbhar* (self-reliance). The MAC curve highlights that in the absence of net-zero fuels and direct RE-based electrification of process heating applications, carbon capture, utilisation, and storage (CCUS) is essential for DAP and OCF decarbonisation, even after using green ammonia. Amongst the techniques considered, carbon offset through afforestation has not been assigned any number due to significant uncertainties in its mitigation costs.

B. Key recommendations

- **Incentivise the adoption of the best-available EE technologies through the Indian Carbon Market.** The *Indian Carbon Market* (ICM) and *Perform, Achieve, and Trade* (PAT) schemes can play a pivotal role in promoting the uptake of EE technologies (Bureau of Energy Efficiency n.d.). EE measures can potentially mitigate 10 per cent of emissions from the fertiliser industry and improve operational efficiency. Hence, EE technologies should be encouraged.
- **Incentivise RE uptake in the fertiliser sector.** The Government of India should promote the adoption of RE by providing financial and policy support, such as waivers or reductions in open access charges. This approach would facilitate the industry's transition to cleaner energy sources.
- **Blend green ammonia in the fertiliser industry.** Promoting green ammonia can have transformative effects as ~35 $MtCO_2$ can be abated. Notwithstanding the economic feasibility challenges, a gradual and phased approach to adopt green ammonia blending can emerge as a viable solution.
- **Promote the use of green ammonia for the production of green urea ammonium nitrate.** Urea ammonium nitrate (UAN) is a popular liquid fertiliser that is widely used in North America and Europe. It is produced by blending ammonium nitrate (AN) with urea. AN produced from green ammonia can be blended with urea to produce green UAN.
- **Co-locate bioethanol and urea plants.** CO_2, available from bioethanol as a by-product, can be used to produce urea. To achieve the revised target of blending 20 per cent of bioethanol in petrol by 2025, new bioethanol plants need to be established, and these new plants can be located near urea plants.

1. Introduction

Fertilisers play a crucial role in the Indian agricultural sector and are essential for ensuring food security. With the growth of the Indian population, the demand for agricultural products; therefore, along with selecting the right food crops, the fertiliser sector has been pivotal in India's drive to achieve food security. The Indian fertiliser industry dates back to 1943, when Fertilisers and Chemicals Travancore Limited (FACT) incorporated the first large-scale fertiliser plant in Udyogamandal, Kerala (Department of Fertilizer n.d.). Enabled by the Green Revolution of the 1960s, India witnessed rapid growth in agricultural production and productivity, fuelled by the increased accessibility of affordable fertilisers to farmers (Chand and Singh 2023).

Over the years, many new fertiliser plants were established to meet the continuously growing domestic demand. Six public-sector undertakings (PSUs), two public–private partnerships, and several private players operate over 150 plants across India, with an annual production capacity of 60 million tonnes per annum (MTPA) (Fertilizer Association of India 2023). Fertiliser consumption in India has accelerated since the Green Revolution, both in terms of per hectare agricultural area and per capita consumption, from ~2 kg per hectare in the 1960s to ~150 kg per hectare in 2021–22 (Fertilizer Association of India 2023).

With a total production of ~50 million tonnes (MT), India's total fertiliser production stood at ~20 per cent of global fertiliser production in 2022–23. The total greenhouse gas emissions produced by India's chemicals and fertilisers industry are about 75 MTPA, which constitutes around 12 per cent of India's industrial energy use emissions (Biswas, Ganesan and Ghosh 2019).

> Green ammonia use in the urea sector alone can abate ~30$MtCO_2$.

1.1 The fertiliser industry at a glance

Fertilisers are chemical products added as external agents to address nutrient deficiencies in the soil by providing (a) primary nutrients (nitrogen, phosphorus, and potassium), (b) secondary nutrients, and (c) various micronutrients essential for plant growth. Fertilisers can be categorised into (a) straight fertilisers (nitrogenous, phosphatic, potassic) and (b) complex fertilisers – a combination of nitrogen and phosphorus (NP) or nitrogen, phosphorus, and potassium (NPK). The Indian fertiliser product mix mainly includes urea, di-ammonium phosphate (DAP), other complex fertilisers (OCF), ammonium sulphate (AS), and single super phosphate (SSP).

In 2022–23, the global fertiliser production stood at ~218 MT, of which urea alone comprised ~184 MT (Fertilizer Association of India 2023). China and India are the two largest urea producers, accounting for over 55 MTPA and 28.5 MTPA, respectively; together, they contribute approximately 40 per cent of global urea production (International Fertilizer Association 2022). While China is self-sufficient in urea production, India is the second-largest importer after Brazil (Yara 2022), importing 10 MT of urea (Ministry of Commerce and Industry n.d.)

The situation is similar in DAP production, where India contributes ~13 per cent (4.35 MT) of the world's 33.5 MT of DAP production (Department of Fertilizer 2023). This contribution could have been much more significant, but due to the non-availability of phosphate rock, an essential raw material in the DAP production process, India cannot utilise nearly half of its total DAP production capacity of 7.7 MTPA, as it depends on imports for raw materials (ammonia, phosphoric acid/rock phosphate, and sulphur). In addition, this domestic DAP production is highly import-dependent since 90 per cent of the phosphate rocks are imported (PIB 2021), and nearly all (80–90 per cent) non-urea fertiliser plants depend on imported ammonia; only a few (10–20 per cent) use natural gas. Therefore, to meet its domestic demand, India further imports 6.7 MT of DAP.

Production of OCFs also involves similar challenges; of the 15.6 MT of OCFs consumed in India in 2022–23, 5.6 MT (approximately 35 per cent) were imported. This is despite India over utilising its OCF production capacity of 8.72 MT with an annual production of 10 MT.

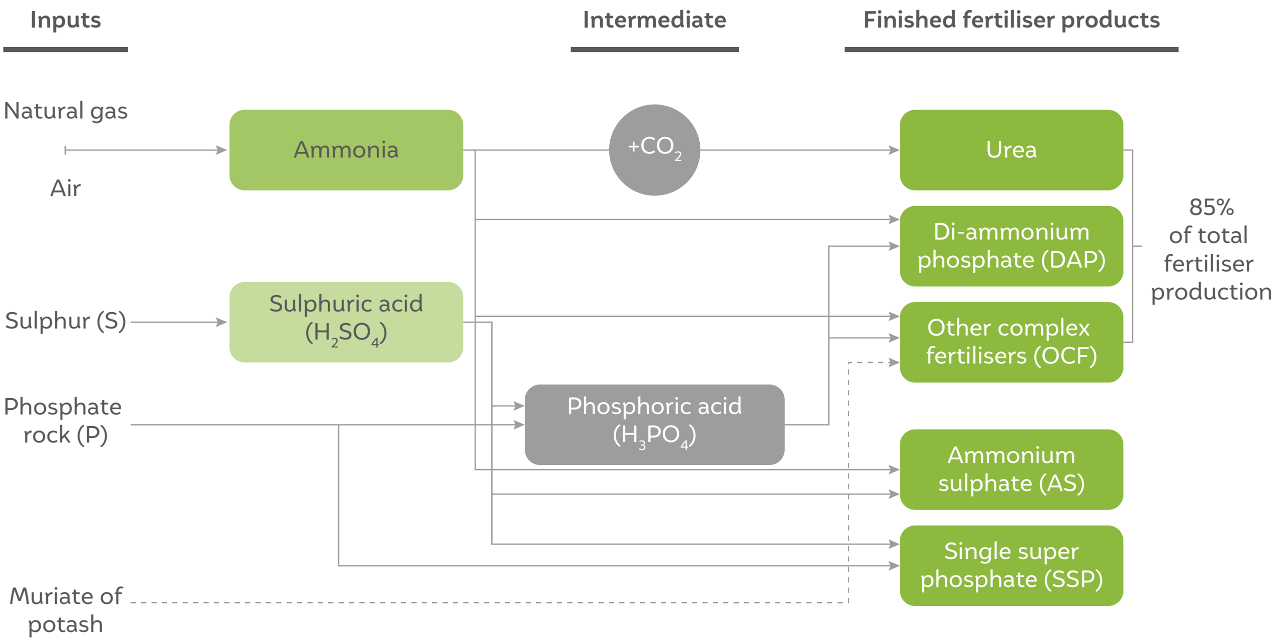
Table 1 highlights the status of India's fertiliser production capacity, demand, and imports. The data clearly show that production at urea and OCF plants exceeds the 100 per cent installed capacity to limit the energy consumption and to meet the demand.

Table 1 Finished fertiliser products and production in India for 2022–23

Finished fertiliser Product	Production (MT)	Production Share (%)	Installed capacity (MT)	Imports (MT)	Consumption (MT)
Urea	28.50	57.7	28.1	10.16	35.7
DAP (di-ammonium phosphate)	4.35	8.8	7.7	6.68	10.4
OCF (NP/NPK)	10.03	20.3	8.72	5.6	15.6
AS (ammonium sulphate)	0.86	1.7	0.763	-	0.76
SSP (single super Phosphate)	5.65	11.4	12.32	-	5.02
Total fertiliser	**49.38**	**100**	**57.6**	**22.4**	**67.6**

Source: Department of Fertilizer. 2023. Annual Report. Government of India, Fertilizer Association of India. 2023. Fertilizer statistics. FAI.

Figure 1 Urea, DAP, and OCFs account for 85% of the total fertiliser production in India



Source: Authors' compilation

Figure 1 shows the components used in the manufacture of the different types of fertilisers produced in India. Urea, a nitrogen-rich fertiliser, uses ammonia (NH_3) and carbon dioxide (CO_2), which are produced using natural gas as feedstock. Similarly, DAP, a phosphate-rich fertiliser, is produced using ammonia and phosphoric acid, and OCFs are produced using ammonia, phosphoric acid, and MOP (muriate of potash) in different ratios depending on the grade of NPK to be produced.

Apart from urea, DAP, and OCFs, other fertiliser products are used in India, such as ammonium sulphate (produced by steel plants as a by-product of coke oven gas) and single super phosphate (produced by treating finely ground rock phosphate with sulphuric acid (H_2SO_4). The emissions from these processes are negligible compared to those from urea, DAP, and OCF production. In addition, ammonium sulphate accounts for less than 2 per cent of the total fertiliser output. Single super phosphate, accounting for ~10 per cent of the total production (Department of Fertilizer 2023) has a specific energy consumption (SEC) of ~0.12 GCal/t-SSP (Paradeep Phosphates Limited 2017), which is much lower than that of urea at 5.65 GCal/t-urea. Given its significantly lower emissions, it has not been included in our assessment. Therefore, for our analysis in this report, we considered only urea, DAP, and OCFs, which account for ~85 per cent of the total fertiliser production in India.

1.2 Energy consumption in the fertiliser industry

The production of fertilisers, particularly urea, is an energy-intensive process that relies on the use of fossil fuels both as fuel and feedstock. Urea production is highly thermal energy intensive because the reactants need to be brought to the required temperature and pressure. It also requires fuel to generate steam and power, which is needed during the production process. Electricity is produced in-house using natural gas, fuel oil, or coal or is sourced from the grid. In the case of urea production, natural gas has taken over as the primary feedstock in fertiliser plants, replacing fuel oil and naphtha. About 70 per cent of natural gas is used as a process gas, and the balance is used as fuel gas (Liu, Elgowainy and Wang 2020). As per the *New Urea Policy, 2015*, ~85 per cent of Indian fertiliser plants were dependent on natural gas. A recent assessment shows that all urea plants now use natural gas as feedstock (Department of Fertilizer n.d.), which aligns with the Indian government's push to reduce energy consumption and lower emissions in the fertiliser industry.

Figure 2 shows the production and installed capacity of urea, DAP, and OCF plants, along with their respective plant locations. Most urea plants in India have an SEC of 5–8 GCal/t-urea and an overall weighted average SEC of 5.65 GCal/t-urea.

The *New Urea Policy, 2015*, classified 13 urea units (having preset energy norms between 5.0 and 6.0 GCal/t-urea) under Group I, 4 units (with preset energy norms between 6.0 and 7.0 GCal/t-urea) under Group II, and 8 units (with preset energy norms more than 7.0 GCal/t-urea) under Group III. Groups I, II, and III are mandated to achieve the target energy norm (TEN) of 5.5, 6.2, and 6.5 GCal/t-urea, respectively. Three naphtha-based units, on converting it to natural gas, are required to achieve a TEN of 6.5 GCal/t-urea. The six recently commissioned, large-capacity (3850 tonnes per day), state-of-the-art urea plants are designed with an SEC of 5.0–4.9 GCal/t-urea. Further, the BVFCL plants that are high in energy consumption are proposed to be closed in order to install new units that will be highly energy efficient.

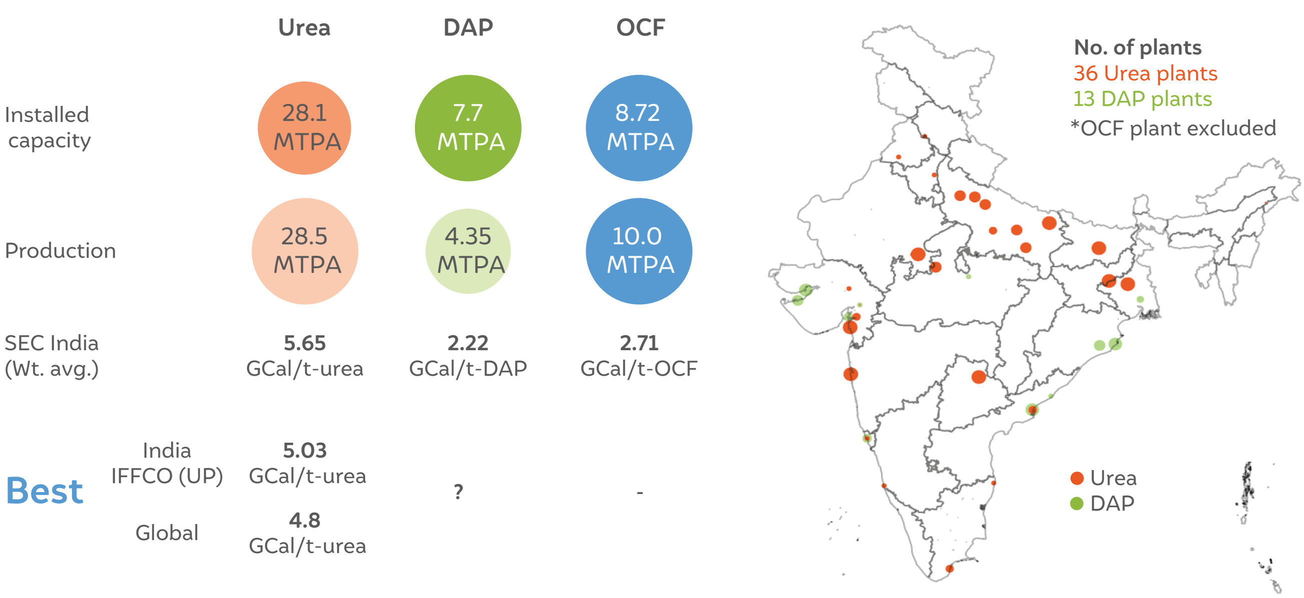
The urea units that were able to invest in energy-saving schemes have achieved their TEN; however, it would not be economical for the vintage units (pre-1982) and units with poor financials to invest in energy-saving schemes.

According to the Fertiliser Association of India, energy accounts for 90 per cent of the variable cost in producing ammonia, and ammonia accounts for 80 per cent of energy consumption in the production of urea (Nand and Goswami 2021). Energy consumption norms are a major parameter used in calculating the reimbursement of costs in the government's urea pricing and subsidy policy, and these norms have been periodically revised downwards. Consequently, the weighted average energy consumption in urea plants has reduced from 8.87 GCal/t-urea in 1987–88 to 5.65 GCal/t-urea in 2022-23. This may further go down following investments in energy-saving schemes and the commissioning of new large-capacity ammonia/urea plants. For instance, the IFFCO Aonla II unit in Uttar Pradesh has the lowest SEC of 5.03 GCal/t-urea production in India (excluding newly commissioned revival projects).

Studies have shown that the best plants globally have achieved an SEC of 4.8 GCal/t-urea (Casale 2024). However, in the Indian context, due to the presence of a large number of vintage plants, further reduction in the SEC would be difficult to achieve using conventional energy-saving schemes.

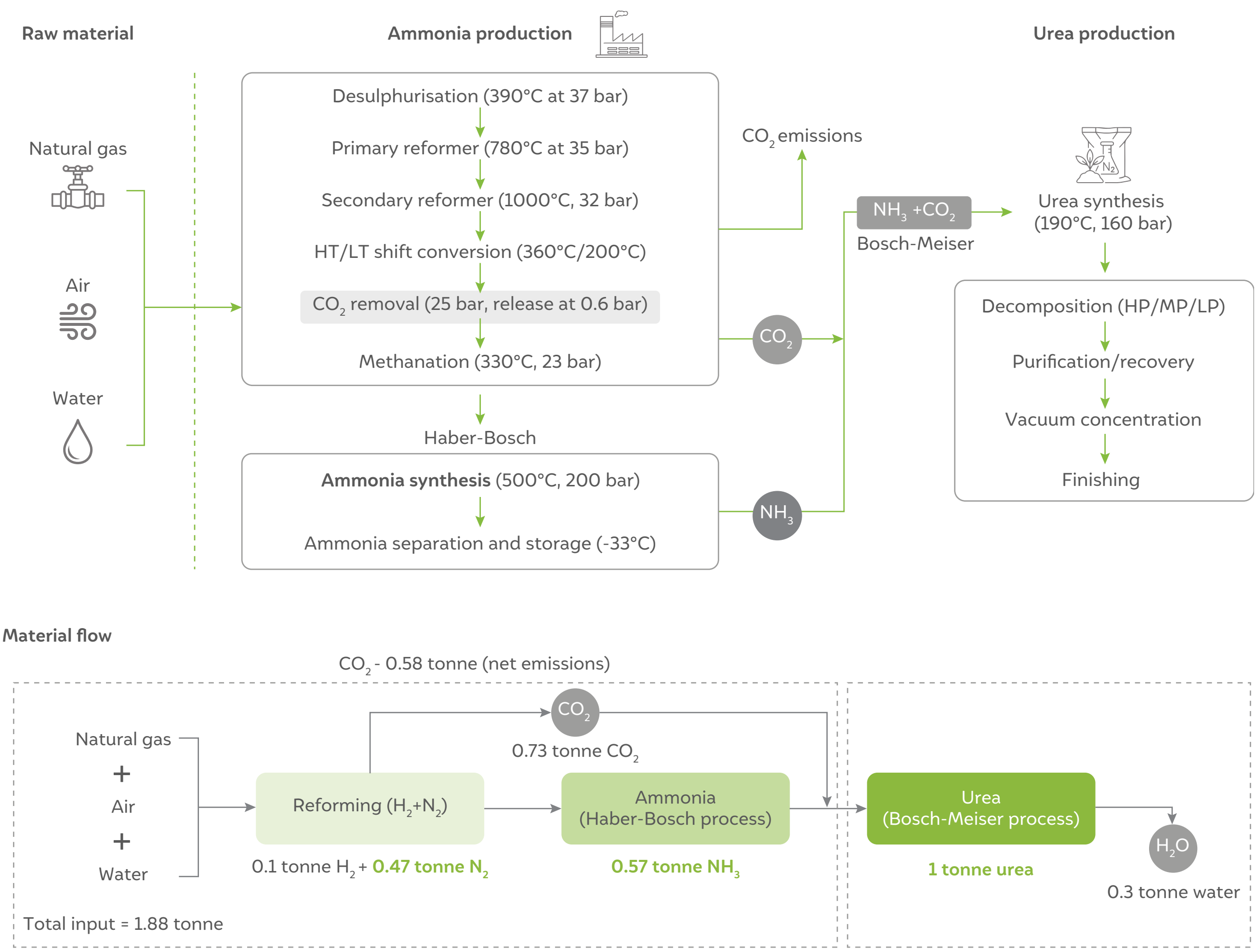
In our study, the SEC values of DAP and OCF were estimated as 2.15 GCal/t-DAP and 2.72 GCal/t-OCF, respectively, of which ~90 per cent is the energy associated with producing the ammonia used in the process. Industry experts indicate that 80–90 per cent of the ammonia used in DAP and OCF production is imported. In 2022–23, India imported 2.3 MT of ammonia, where DAP and OCF units consumed 3.4 MT of ammonia for producing fertilisers (Ministry of Commerce and Industry n.d.). Nonetheless, to calculate the SEC values and baseline emissions from DAP and OCF production, the emissions from the use of imported ammonia have been attributed to the plant for simplicity of assessment.

Figure 2 **Specific energy consumption and geographical location of urea and DAP plants**



Source: Authors' analysis

Figure 3 General urea production process and mass balance



Source: Authors' analysis based on industry inputs

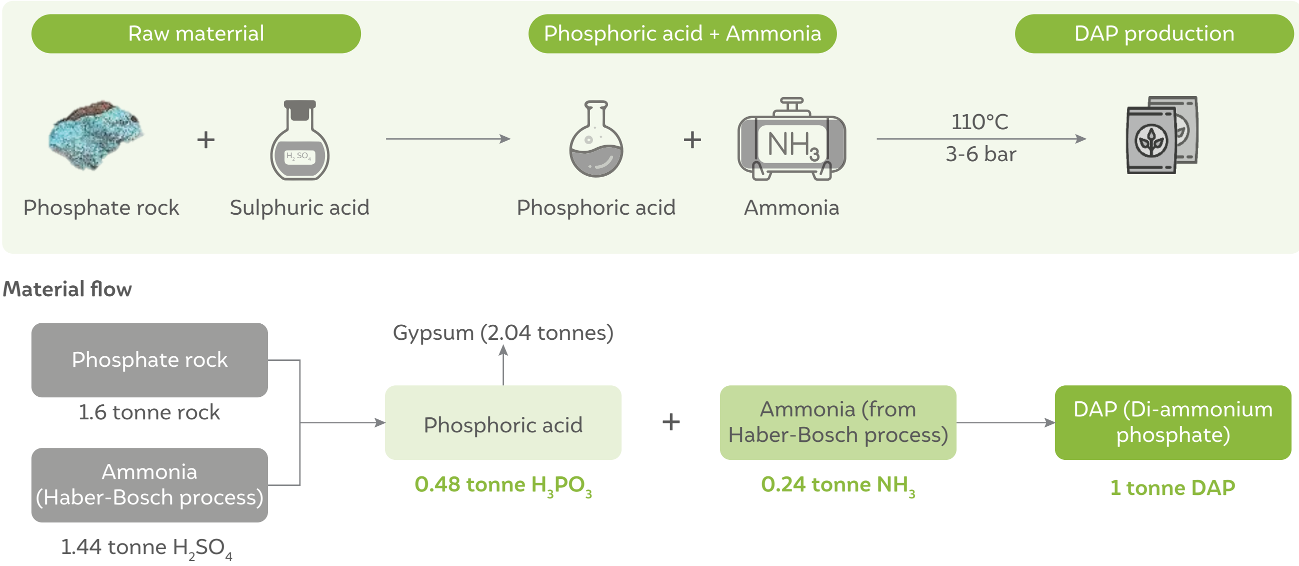
1.3 Production processes

Nitrogenous fertilisers such as urea, NP, and NPK require ammonia as a key raw material, and the production process is highly energy-intensive. The production of ammonia involves reactions that are exothermic and endothermic. This offers an opportunity for the recovery of waste heat and its utilisation in the process itself. Ammonia plants are normally located in complexes with urea manufacturing facilities. This is because all the major raw materials required for the production of urea (ammonia, steam, and CO_2) are obtained from the operation of the ammonia plant. In this section, we summarise the high-level manufacturing processes used for the three fertilisers under consideration to estimate the emissions from their respective manufacturing processes and develop the marginal abatement cost (MAC) curve.

- **Urea:** Urea production involves two steps: the production of ammonia and then its reaction with carbon dioxide (CO_2) to produce urea. Ammonia is produced predominantly from natural gas using the Haber–Bosch process, where nitrogen (N_2) and hydrogen (H_2) are reacted at a high temperature and pressure in the presence of a catalyst to produce ammonia. Hydrogen is obtained during the steam methane reforming of natural gas, and nitrogen is introduced as air during the secondary reforming process (Topsoe n.d.). During this process, CO_2 is produced as a by-product, extracted from the process gas, and used in the production of urea. Urea is produced using the Bosch–Meiser process, where ammonia and CO_2 are reacted at a high temperature and pressure to produce ammonium carbamate ($NH_2CO_2NH_4$), which is dehydrated and cooled in a prilling tower to obtain granulated/prilled urea (NH_2CONH_2). Figure 3 summarises the steps for producing urea and also indicates the material balance. The urea formation reaction is as follows:

$$2NH_3 + CO_2 \rightarrow NH_4CO_2NH_2$$
$$NH_4CO_2NH_2 \rightarrow (NH_2)CO(NH_2) + H_2O$$

Figure 4 DAP production process with the material balance



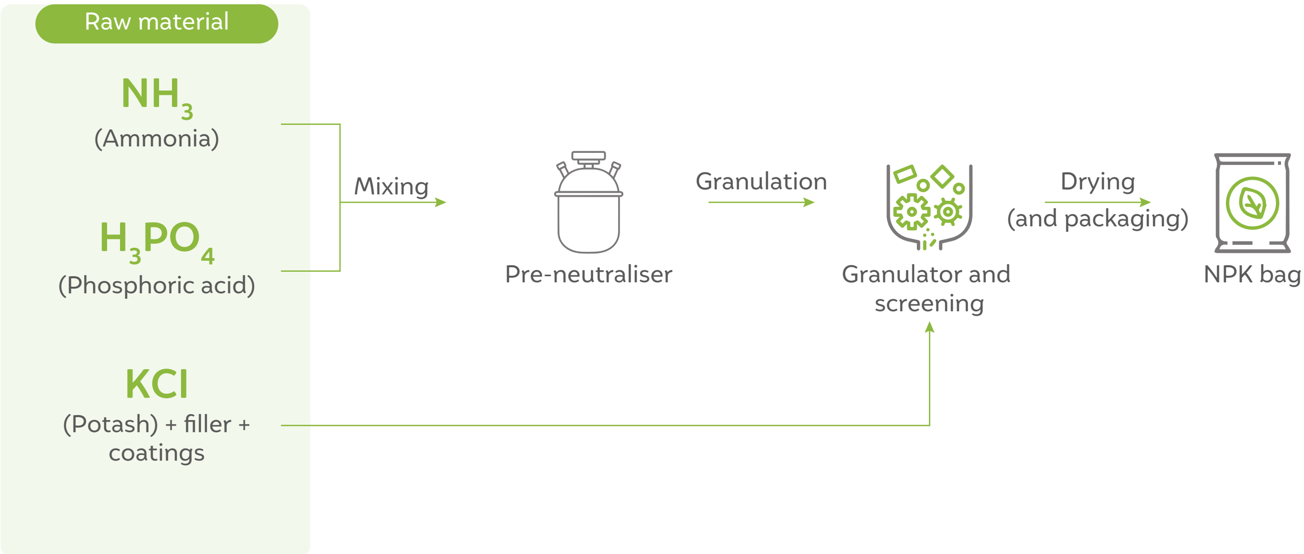
Source: Authors' analysis

- **DAP:** Di-ammonium phosphate (18:46:0) is a fertiliser consisting of 18 per cent nitrogen nutrient and 46 per cent phosphate (P_2O_5) nutrient. DAP production takes place in two steps. In the first step, phosphate rock, rich in phosphorus pentoxide (P_2O_5), reacts with sulphuric acid (H_2SO_4) to produce phosphoric acid (H_3PO_4). In the next step, the phosphoric acid is mixed with ammonia in a reactor chamber at ~110°C to produce DAP. Ammonia for DAP is normally obtained from external sources, as it is not economical to produce ammonia in-house. Figure 4 highlights the process and material flow during the DAP production process. DAP formation is given by the following reaction equation:

$$H_3PO_4 + 2NH_3 \rightarrow (NH_4)_2HPO_4$$

- **OCFs:** The manufacturing process of OCFs is similar to that of DAP, with the only difference being the addition of potash/other nutrients into the ammoniator/granulator. The process energy consumed is also similar to that of DAP, but the quantity of ammonia required in the process varies depending on the grade of fertiliser being prepared. OCFs are essentially a mixture of ammonia, phosphate rock, and potash in specific ratios that can provide the desired amount of nitrogen (N), phosphorus (P), and potassium (K). NPK are often mixed with micronutrients to meet soil nutrient deficiencies. Additionally, coatings and fillers such as silica, clay, limestone, and sulphur are added to improve the physical characteristics of the fertiliser, prevent caking, and provide additional nutrients. Some of the essential NPK-based fertilisers produced in India include MAP (monoammonium phosphate), NPK 12:32:16, NPK 16:20:0, and NPK 16:16:16. Figure 5 represents the conventional production process for OCFs.

Figure 5 OCFs are a mixture of NPK blends, with 20+ types of grades being produced in India



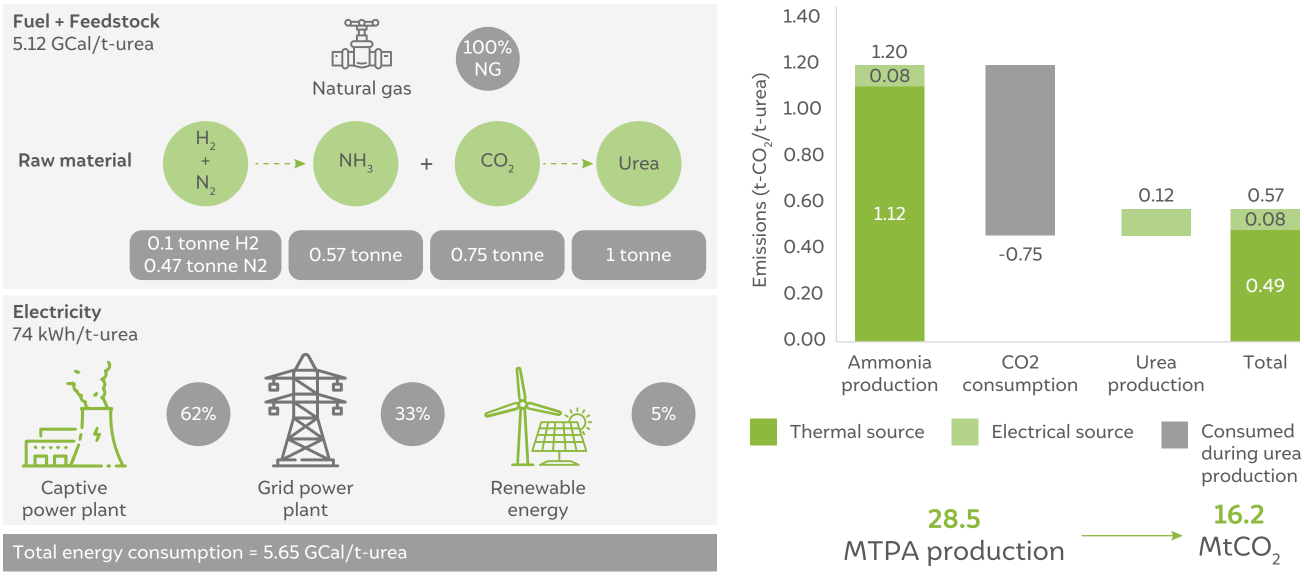
Source: Authors' analysis

2. Baseline emissions and energy requirements

Natural gas used as feedstock and as a thermal energy source is the primary source of emissions in fertiliser plants. Electrical energy usage also contributes to a small share of the emissions. We use these thermal and electrical energy consumption data to create the baseline for emissions in the fertiliser manufacturing process. FY 2022–23 was selected to estimate the emissions, representing the latest available published data. The analysis included 36 ammonia/urea units in the country, including four newly commissioned revival projects.

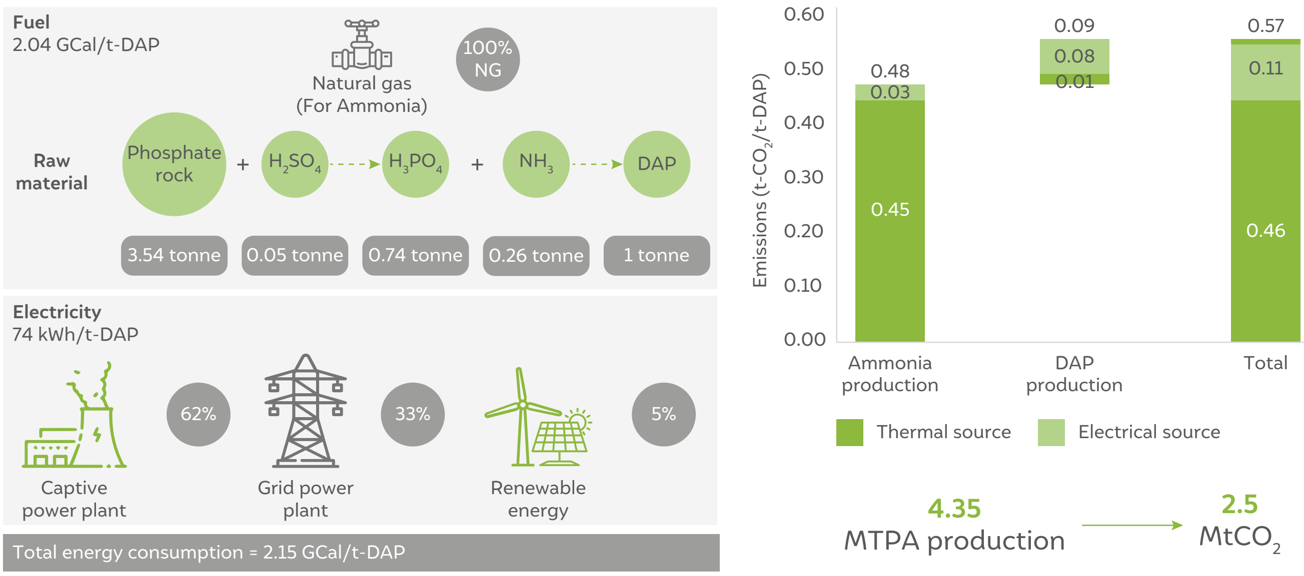
In this study, we considered only scope 1 and scope 2 emissions for fertiliser production. Figure 6 depicts the SEC (thermal and electrical) and emission intensity during urea production. For simplicity, it is assumed that all the thermal energy consumed is obtained from natural gas use. In contrast, electricity consumed in the production process is sourced from a mix of coal-based captive power plants (CCP), the electrical grid, and renewable power in the ratio of 62:33:5 (Central Electricity Authority 2020). As highlighted in Figure 6, 1.20 tonnes of CO_2 is emitted during the Haber–Bosch process for each tonne of urea produced. A significant portion of this CO_2 is used in the Bosch–Meiser process for producing urea. Although 0.73 t-CO_2/t-urea is required as per stoichiometry, we assume that 0.75 t-CO_2/t-urea is internally consumed (considering the process losses) for producing urea. Additionally, thermal energy is also utilised to maintain the reaction temperature and pressure in this step, which results in 0.12 t-CO_2 of emissions. The emissions from power consumption are 0.08 t-CO_2/t-urea. Thus, the resulting net emissions from urea production is 0.57 t-CO_2/t-urea. For the 28.5 MTPA of urea produced annually, the total emissions are estimated to be approximately 16.2 MtCO_2 (~11 MtCO_2 from natural gas used as feedstock and the rest from fuel used to generate thermal energy).

Figure 6 Baseline SEC values and emission intensities for urea plants in India



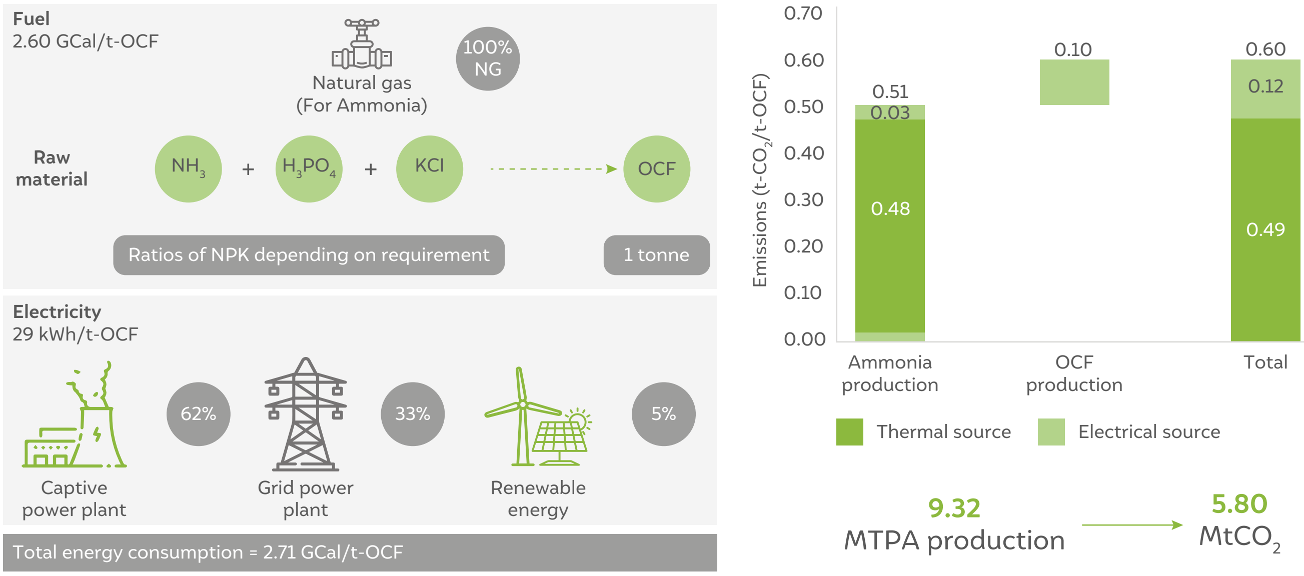
Source: Authors' analysis

Figure 7 Baseline SEC values and emission intensities for DAP plants



Source: Authors' analysis

Figure 8 Baseline SEC values and emission intensities for OCF plants



Source: Authors' analysis

Figure 7 shows the SEC and emissions calculated for DAP production. Our assessment indicated that DAP production has an SEC of 2.15 GCal/t-DAP, resulting in baseline emissions of 0.57 t-CO_2/t-DAP. Approximately 80 per cent of these emissions are associated with thermal energy use, and ~85 per cent, with ammonia production. The comprehensive emissions from the total DAP production of 4.35 MT in India are estimated to be approximately 2.5 $MtCO_2$ annually.

There are no official or peer-reviewed emissions data available for OCF production. Industry experts suggest that the OCF production process is similar to that of DAP. Hence, the emissions and SEC for OCFs were estimated assuming a similar production process to that of DAP with the additional assumption that OCFs require a higher amount of ammonia than DAP since there are various grades of ammonia-rich OCFs. With this assumption, the baseline emission was estimated to be 0.60 t-CO_2/t-OCF. Figure 8 summarises the SEC and total emissions of 6.1 $MtCO_2$ from OCF production in India. Annexure I summarise the parameters used for the SEC and emission calculations.

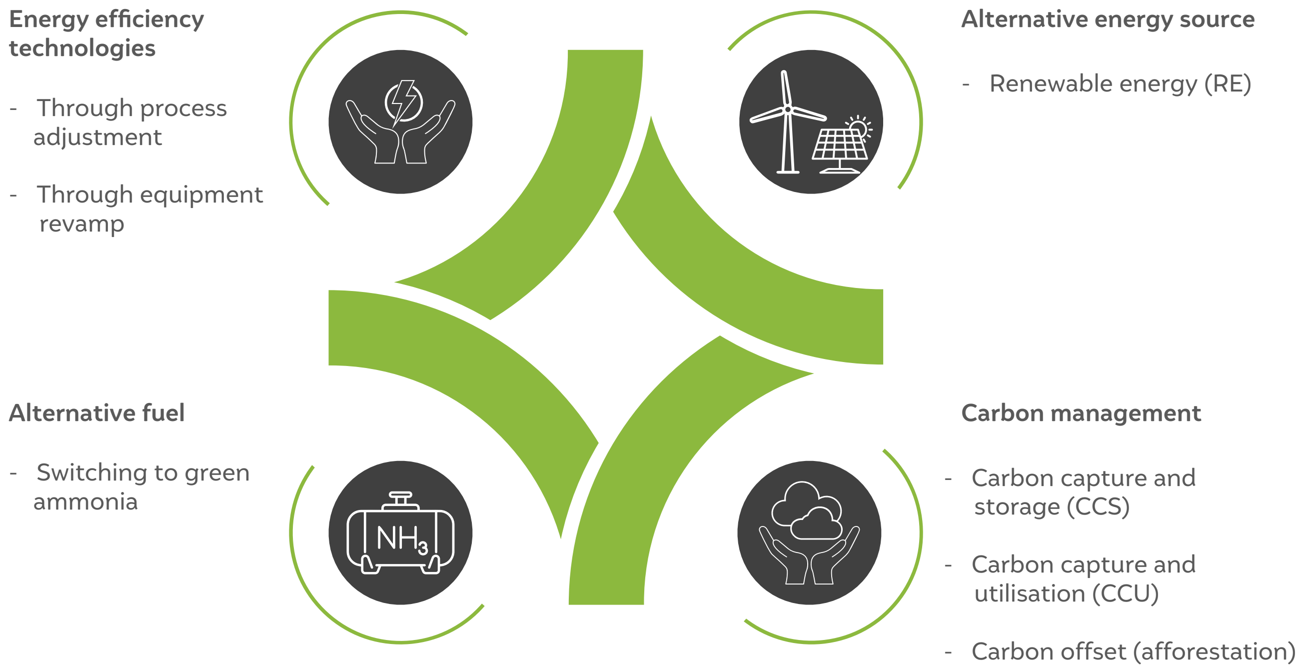
3. MAC estimation methodology

Marginal abatement cost (MAC) is a concept used in environmental economics and climate policy to measure the cost of reducing each additional unit of CO_2 emission. It represents the cost of implementing a specific emission reduction measure or technology. As shown in Figure 10, our analysis considers various technologies to calculate the MACs, and they can be categorised into the following four groups:

- Energy efficiency: This involves reducing energy consumption while simultaneously enhancing the output or performance of the processes, thus leading to lower energy costs.
- Alternative energy source: Renewable sources of electricity can be used to meet energy demands and offset fossil captive or grid power consumption.
- Alternative fuel: This decarbonisation lever involves switching to green ammonia instead of grey ammonia.
- Carbon management: It involves mitigating emissions through carbon capture and storage (CCS), carbon capture and utilisation (CCU), and carbon offset mechanisms such as afforestation.

These four categories are relevant to the fertiliser sector, encompassing improvements in the ammonia, urea, and DAP and OCF plants. Table 2 shows various options that can be implemented to decarbonise the fertiliser sector.

Figure 10 Carbon abatement options for the fertiliser sector

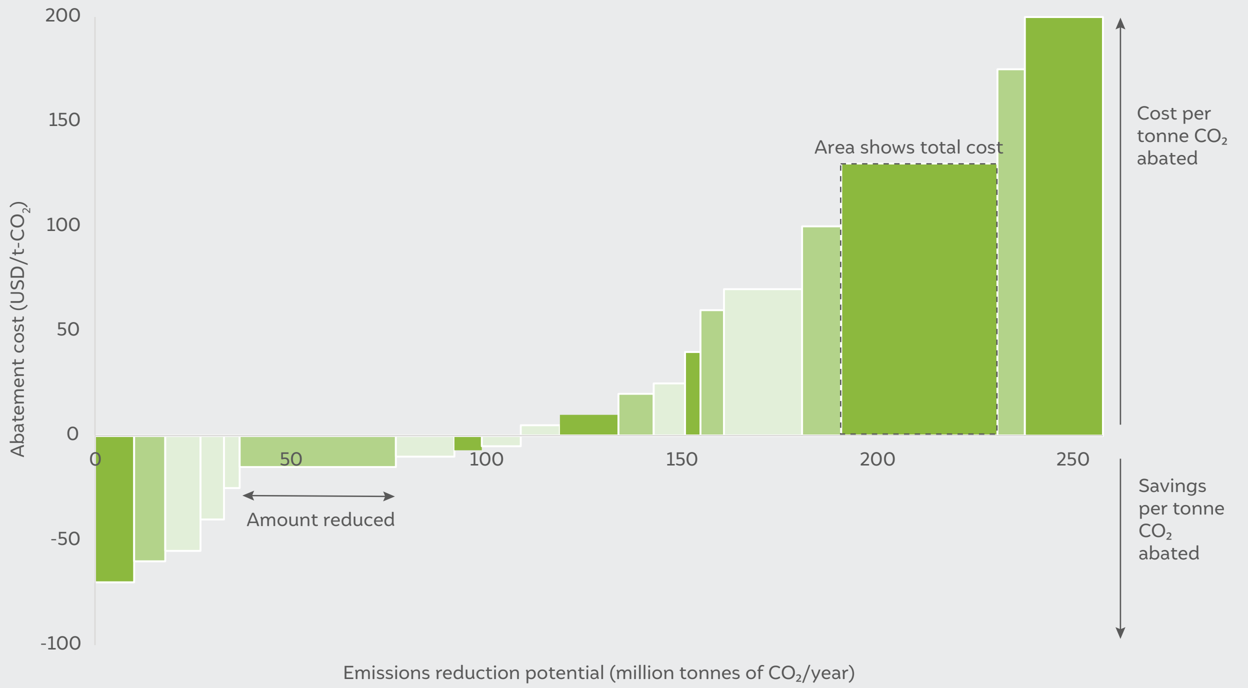


Source: Authors' analysis

Box 1 **Utility of MAC curves**

The MAC curves are generated by plotting the cost of CO2 mitigation (USD/t-CO2) for a specific carbon mitigation technology on the y-axis against that technology's total mitigation potential (t-CO2) on the x-axis. Figure 9 illustrates the schematic of a standard MAC curve. The mitigation cost spectrum ranges from negative to positive values. A negative cost signifies a net economic benefit from deploying a particular technology, while a positive cost implies additional expenses incurred for the technology. The cumulative x-axis values denote the total CO2 emissions over a specified period.

Figure 9 **Schematic of a typical MAC curve**



Source: Authors' analysis

Source: Authors' analysis

Table 2 Four pillars to enable net-zero carbon emission in the fertiliser sector

Parameters	Ammonia plant	Urea plant	DAP and OCF plant
1. Energy efficiency (reduce specific energy consumption)			
(a) Through process adjustment	Improve waste heat recovery and reduce heat rejection to cooling water	Reduce the flow of inert gas in the reactor	Reduce specific ammonia consumption
	Reduce the steam/carbon ratio	Reduce steam and power requirements	Reduce specific power consumption
	Maximise CO_2 conversion and recovery to reduce the load on the methanator	Improve conversion of ammonia and CO_2 in the reactor	-
	Reduce synthesis loop pressure and increase conversion per pass	Maximise the use of steam available from the ammonia plant	-
	Improve synthesis gas purification to reduce gas circulation	Maximise recovery of waste heat	-
	Reduce make-up gas temperature to reduce compressor power	-	-
(b) Through equipment revamp	Carry out retrofits in compressors to improve efficiency and reduce steam consumption	Improve conversion efficiency in the reactor through retrofits	Improve conversion efficiency of the reactor through retrofits
	Use variable frequency drives	Improve the reliability of plants and reduce breakdowns	Use variable frequency drives
	Use vapour absorption refrigeration (VAR) to cool inlet gas to compressors	Switch small pumps from steam to power drive	Prevent equipment breakdown through preventive maintenance
	Switch small pumps from steam to power drive	Upgrade CO_2 and process air compressor	-
	Use a gas turbo generator or heat recovery steam generator instead of a steam turbo generator for power generation	Prevent equipment breakdown	-
2. Alternative energy source			
(a) Using renewable energy (RE)	Use of RE to meet the electrical power requirement	-	Use of RE to meet the electrical power requirement
3. Alternative fuel			
(a) Sourcing green ammonia	-	Source green ammonia to reduce the specific energy consumption	Substitute grey ammonia with green ammonia to reduce the specific energy consumption
4. Carbon management			
(a) Sourcing CO_2 from a bioethanol plant	Source CO_2 from bioethanol plants instead of operating the ammonia plant at a load more than required (for integrated plants)	Source CO_2 from a bioethanol plant	-
(b) Adopting CCS	Use CCS to capture CO_2 exiting from the furnace/reformer stack	Use CCS to capture CO_2 exiting from the urea reactor	Use CCS to capture CO_2 exiting from dryer stack CPP
(c) Undertaking afforestation to offset balance CO_2 emission	Consider afforestation to offset residual CO_2 emissions	Consider afforestation to offset residual CO_2 emissions	Consider afforestation to offset residual CO_2 emissions

Source: Authors' analysis

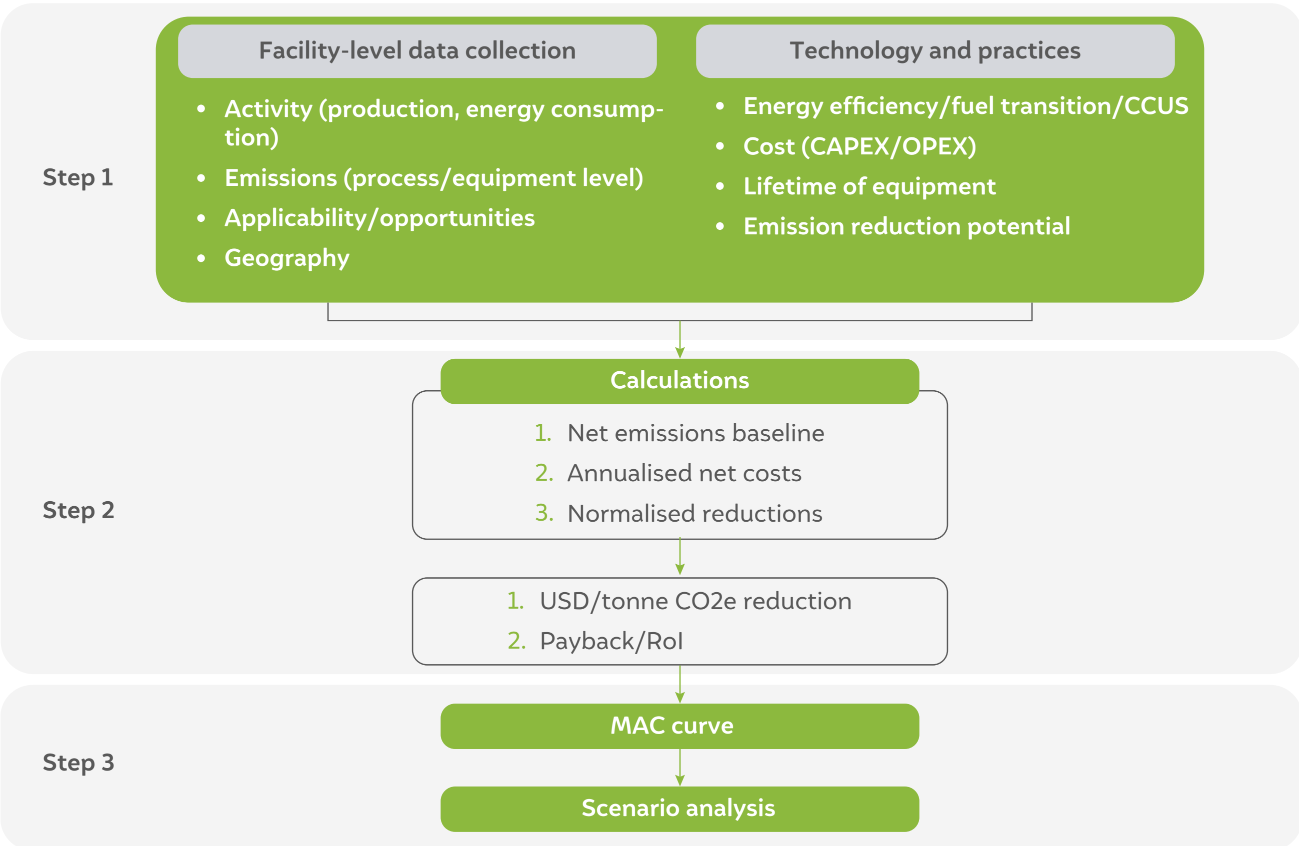
The estimation of MAC for a mitigation technology involves three steps, as shown in Figure 11. The estimated abatement costs for various mitigation options are used to develop the MAC curves.

- Data collection: The first step involves facility-level data collection, which includes data on production, SEC, emissions, fuel use, and so on.
- Emission baseline estimation: The second step involves estimating the emission baseline.
- Financial calculations: In the last step, capital expenditure (CAPEX) and operating expenditure (OPEX) are calculated to estimate the cost of CO_2 mitigation technology.

4. Methodology

The MAC calculations require the costs of raw materials and utilities; the assumed costs are summarised in Table 3. A detailed list of assumptions has been provided in Annexure I. While India imports ~70 per cent of the ammonia consumed in these non-urea fertiliser units (Ministry of Commerce and Industry n.d.), we assume that the ammonia produced in India uses liquified natural gas (LNG) in the manufacturing process. The cost of LNG considered in the assessment corresponds to a grey ammonia cost of approximately USD 360 per tonne. The cost of grey ammonia in the base year of 2022–23 was USD 939 per tonne due to geopolitical turmoil and the post-pandemic recovery. However, we assume that the cost will be approximately USD 360 per tonne in the long run.

Figure 11 MAC estimation methodology



Source: Authors' analysis

Table 3 Major assumptions used in the study to develop the MAC curves

Assumptions	Value	Unit	Remark/References
Cost of natural gas (urea)	7.5	USD/MMBtu	Industry inputs
Cost of natural gas (DAP/OCF)	10.1	USD/MMBtu	Industry inputs
Electricity cost	4.53	INR/kWh	Assumption based on power mix
Cost of grey ammonia (urea)	278	USD/t	Based on the natural gas price
Cost of grey ammonia (DAP/OCF)	357	USD/t	Based on the natural gas price
Cost of green ammonia	700	USD/t	Assumption
Transport cost of CO_2	15	USD/t	(Smith, et al. 2021)
CO_2 capture cost	50	USD/t-CO_2	(IEA 2019)
CCS cost	90	USD/t-CO_2	(Nitturu, et al. 2023)

Source: Authors' analysis

4.1 Energy efficiency in urea production

The data relating to the efficacy of energy efficiency (EE) technologies, their CAPEX and OPEX costs, and their emission mitigation potentials are not available in the literature. However, an extensive analysis of EE technologies in the cement and steel industries revealed that the costs of CO_2 mitigation with EE technologies are similar across hard-to-abate industries (Nitturu, et al. 2023, Elango, et al. 2023). Therefore, we assumed that installation and operations costs, normalised against the energy savings for urea production, are similar to those incurred in cement and steel production. Thus, the combined MAC for all EE measures for fertiliser production was estimated based on the weighted average MACs of various EE technologies with respect to their emissions reduction potential in the cement and steel industries. According to previous CEEW reports for the steel and cement industry, the MAC was calculated at USD -63.5 per tonne of CO_2 for cost-saving EE and USD 49.6 per tonne of CO_2 for expense-driven EE technologies. Subsequently, we calculated the emissions reduction potential of each plant for the MAC curve based on the difference between the plant's own energy consumption and its target SEC. Based on discussions with industry experts, we identified 5.5 GCal/t-urea and 5.3 GCal/t-urea as the targeted emission intensities achievable with cost-saving EE and expense-driven EE, respectively. This approach provided a reduction of ~10 per cent in energy consumption, especially in thermal energy, assuming the average SEC for urea production in India is 5.65 GCal/t-urea. We estimated that 4 per cent (0.02 t-CO_2/t-urea) of the reduction in the emissions intensity of urea fertiliser is achieved through technologies with a negative cost of abatement, while the remaining 6 per cent (0.03 t-CO_2/t-urea) is achieved through EE technologies that have a positive abatement cost.

4.2 Alternative energy sources: renewable energy

Round-the-clock renewable energy (RTC RE) is considered to offset the coal-/gas-based captive power and grid electricity used in fertiliser plants. We obtained the cost of RTC RE based on recent tenders for grid-scale wind–solar–battery hybrid power plants (ReNew 2021). These hybrid power plants, with 400 MW solar power and 900 MW wind power capacity, coupled with 100 GWh of battery storage, can supply 400 MW of RTC RE. Based on the prices and terms of this tender, we assumed that RTC RE power would be available at INR 3.60 per kWh at the generation point, with an 80 per cent annual plant availability. We obtained the landed costs of RTC RE across various fertiliser-producing states, which include a base tariff of INR 3.6 per kWh, a banking charge of INR 2.2 INR per kWh, and an open-access electricity transmission charge from the open-access tariff calculator developed by the CEEW's Centre for Energy Finance (CEEW-CEF n.d.). To estimate the abatement cost of switching from CPP to RE, we considered the electricity tariff from the CPP to be INR 3.72 per kWh and an India-average grid tariff of INR 6.19 per kWh (Nitturu, et al. 2023). We estimated that approximately 280 MW of RTC RE would be needed for the fertiliser sectors considered in the study – namely, urea, DAP, and OCF.

4.3 Alternative fuel: green ammonia

Since ~80 per cent of the emissions in fertiliser production are associated with ammonia production, green ammonia is considered to be one of the primary decarbonising solutions. We assume a green ammonia cost of USD 700 per tonne. If green ammonia is used, the CO_2 required for the Bosch–Meiser process (to produce urea) must be sourced externally. For this purpose, we assume a CO_2 purchase cost of USD 65 per tonne, which includes the cost of CO_2 capture of USD 50 per tonne (IEA n.d.) and a transportation cost of USD 15 per tonne (Smith, et al. 2021). We estimated that the Indian fertiliser sector can consume ~20 MTPA of green ammonia.

4.4 Carbon management

The deep decarbonisation of any industry usually necessitates the use of alternative CO_2 abatement measures, especially CCUS. In the fertiliser industry, carbon management measures play a small but significant role, especially in DAP and OCF production. Using existing natural gas pipeline infrastructure will ensure that issues related to the right-of-way for transporting CO_2 to storage locations can be avoided, and all fertiliser plants can sequester CO_2. In addition, carbon capture has a peak efficiency of 85–90 per cent (while urea plants capture CO_2 with ~99 per cent efficiency). The remaining CO_2 emissions must be mitigated using carbon offset mechanisms such as afforestation.

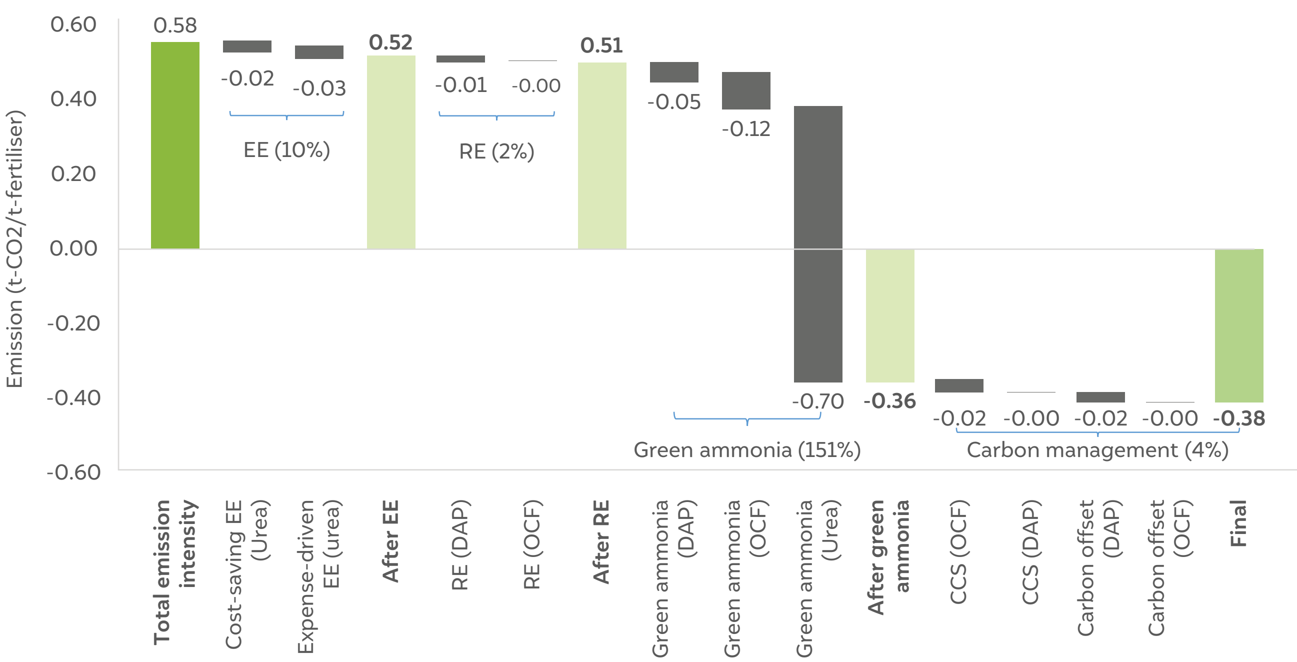
5. MAC for the fertiliser sector

5.1 Emission mitigation trajectory for the fertiliser industry

Figure 12a shows the consolidated emissions mitigation trajectory for the Indian fertiliser industry, where deploying EE measures can reduce emissions by 10 per cent. As fertiliser production requires limited electricity, switching to RE measures results in a mere 2 per cent emissions reduction. However, since ammonia production accounts for ~95 per cent of the emissions, switching from grey to green ammonia results in a 151 per cent emissions reduction, thus resulting in a net-negative fertiliser sector. The negative emissions can be attributed to the need to source CO_2 from other emitters to produce urea. Carbon management options such as CCS, CCU, and afforestation can be adopted as a last resort. Figure 12b shows the individual emissions reduction trajectories for urea, DAP, and OCF.

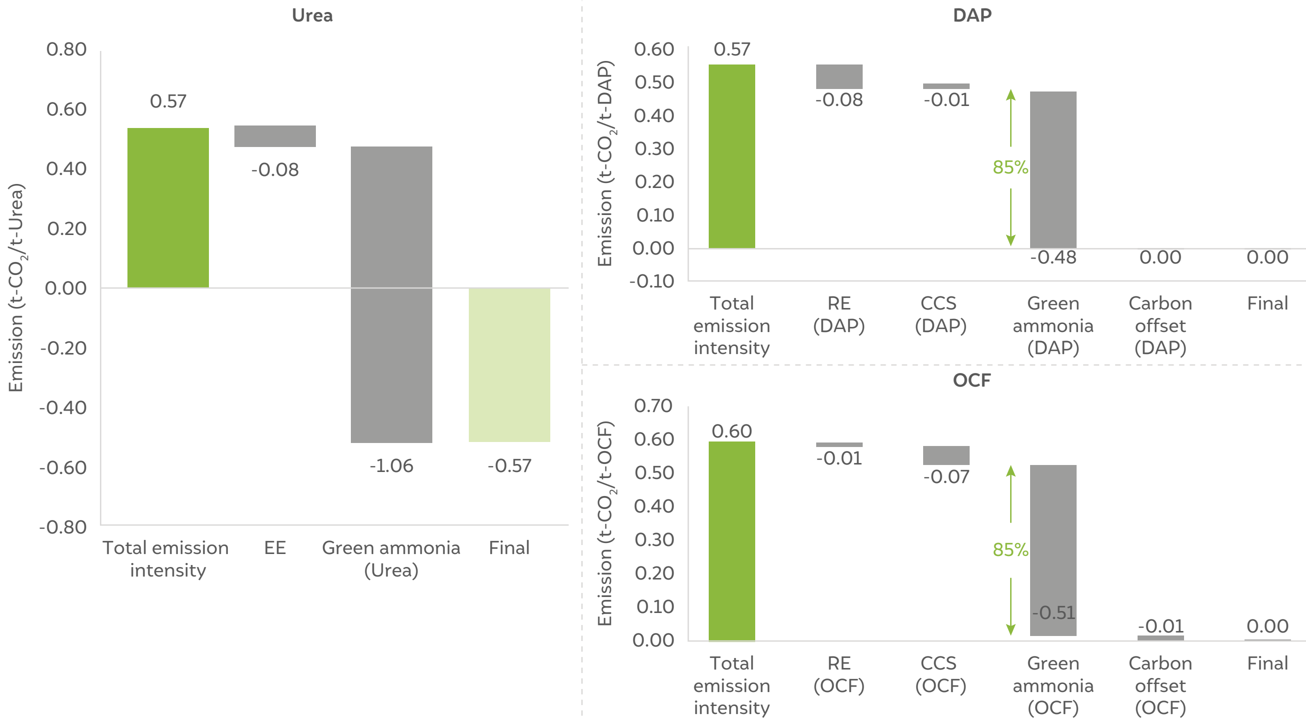
Figure 12 Emission mitigation pathways for the fertiliser industry

a) Consolidated emission mitigation pathway



Source: Authors' analysis

b) Sector-wise emission mitigation pathway for urea, DAP, and OCF



Source: Authors' analysis

5.2 MAC curve for the fertiliser industry

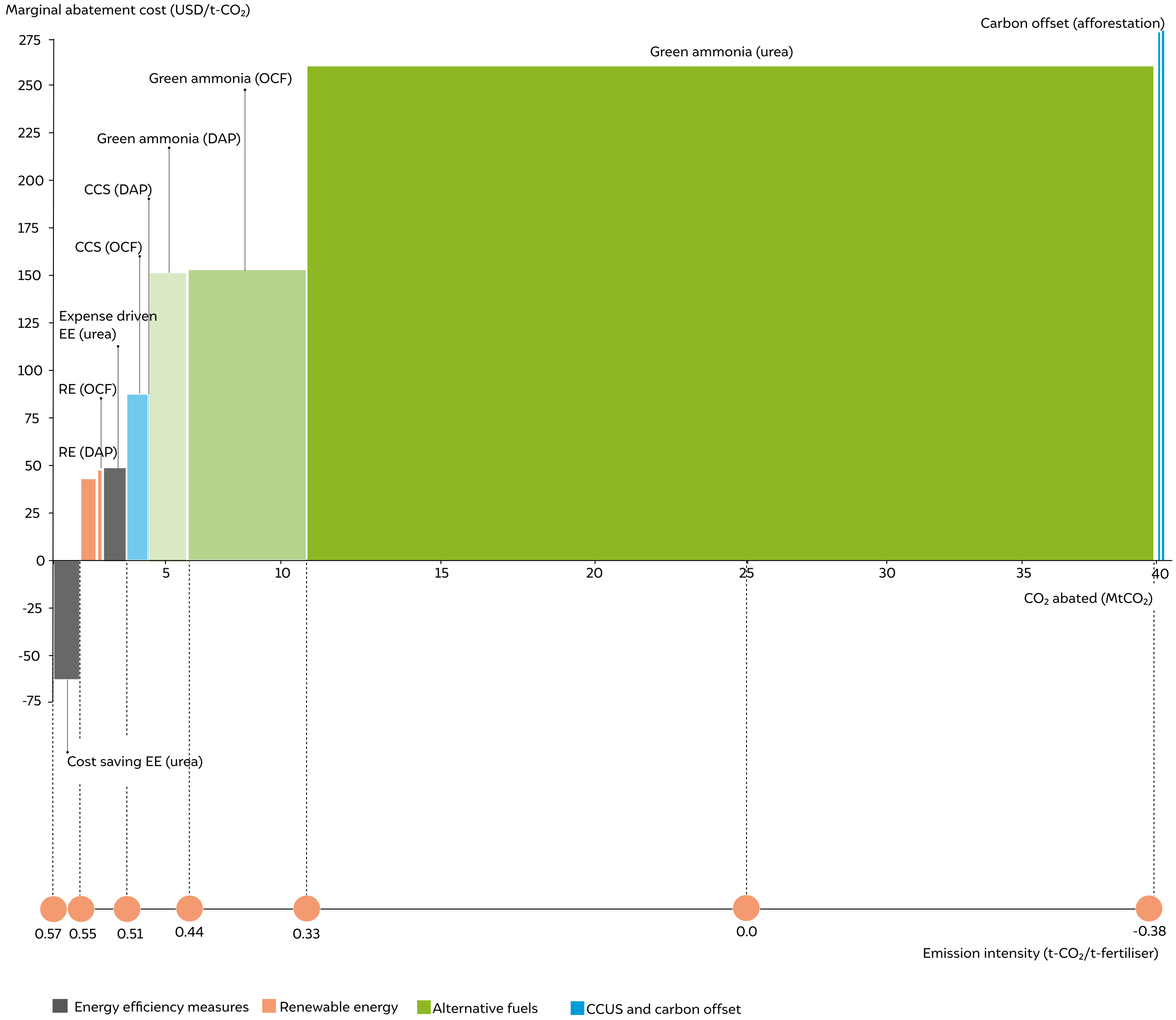
Figure 13 shows the MAC curve for the fertiliser industry, highlighting the pathway to achieve a net-zero fertiliser sector. Currently, the weighted average emissions intensity from fertiliser production stands at 0.58 t-CO_2 per tonne with no mitigation measures in place. The figure shows that cost-saving EE technologies have the lowest mitigation cost of USD -63.5 per tonne. It is also the only cost-saving option in the MAC curve. Expense-driven EE technologies have a MAC cost of USD 49.6 per tonne. Together, the EE technologies can help abate ~2.3 MtCO_2. RE could be another mitigation option, with a MAC of ~USD 45 per tonne, especially for DAP and OCF. Since RE can abate only ~0.4 MtCO_2, it does not have a significant role in decarbonising the fertiliser industry.

As explained in the previous section, green ammonia can make the fertiliser industry a net-negative CO_2 emitter. With a MAC of ~USD 160 per tonne for DAP and OCF and ~USD 270 per tonne for urea, green ammonia can abate 2 MtCO_2 from DAP, 5.1 MtCO_2 from OCF, and 30 MtCO_2 from urea production. The MAC for the use of green ammonia in urea production is higher than that for DAP and OCF production because the urea industry receives subsidised pooled domestic gas priced at USD 7.5 per MMBtu, and we have assumed the use of imported natural gas priced at USD 10.1 per MMBtu for DAP and OCF production.

The lower cost of gas for urea plants translates into a lower grey ammonia cost and, consequently, a higher CO_2 mitigation cost. It is important to note that the total emissions abated by using green ammonia alone in the urea sector is ~30 MtCO_2, which is more than the current level of total emissions from the urea sector, which stands at ~16 MtCO_2. This is because urea production needs CO_2, which is sourced from other sectors, making the fertiliser industry a net-negative industry.

In the scenario where carbon management measures are implemented, the MAC for CCS for DAP and OCF is estimated at USD 90 per tonne, which has the potential to abate 0.006 and 0.13 MtCO_2 for DAP and OCF, respectively. Urea plants do not need any CCS as the entire CO_2 abatement can happen with EE, RE, and green ammonia. It should be noted that while CCS has a lower abatement cost than green ammonia, the MAC curve reflects emissions mitigation through the use of green ammonia primarily because the cost of green ammonia is expected to decrease in the future and support India's ambitions of becoming *Aatma Nirbhar*. The MAC curve highlights the fact that, in the absence of net-zero fuels or direct RE-based electrification of process heating applications, CCUS is essential for DAP and OCF decarbonisation even if green ammonia is used. Amongst the techniques considered, carbon offset through afforestation has not been numerically estimated due to significant uncertainties in its mitigation costs.

Figure 13 Cumulative MAC for the fertiliser sector



Source: Authors' analysis

6. Sensitivity analysis

In the base case, we considered pre-pandemic energy prices to negate the effect of low-price distortions during the pandemic and significantly higher prices after it during FY 2022–23. Table 4 shows the parameters considered for the sensitivity analysis, which essentially reflects the higher prices of natural gas in the fertiliser sector. Here, the cost of grey ammonia is estimated at ~USD 500 per tonne for DAP and OCF production and ~USD 400 per tonne for urea production. A separate study is needed to quantify the impact of a change in the prices of green and grey ammonia on the cost of mitigation using EE technologies. Therefore, in this study, we assumed that the mitigation costs for EE technologies remain the same across the base and sensitivity cases.

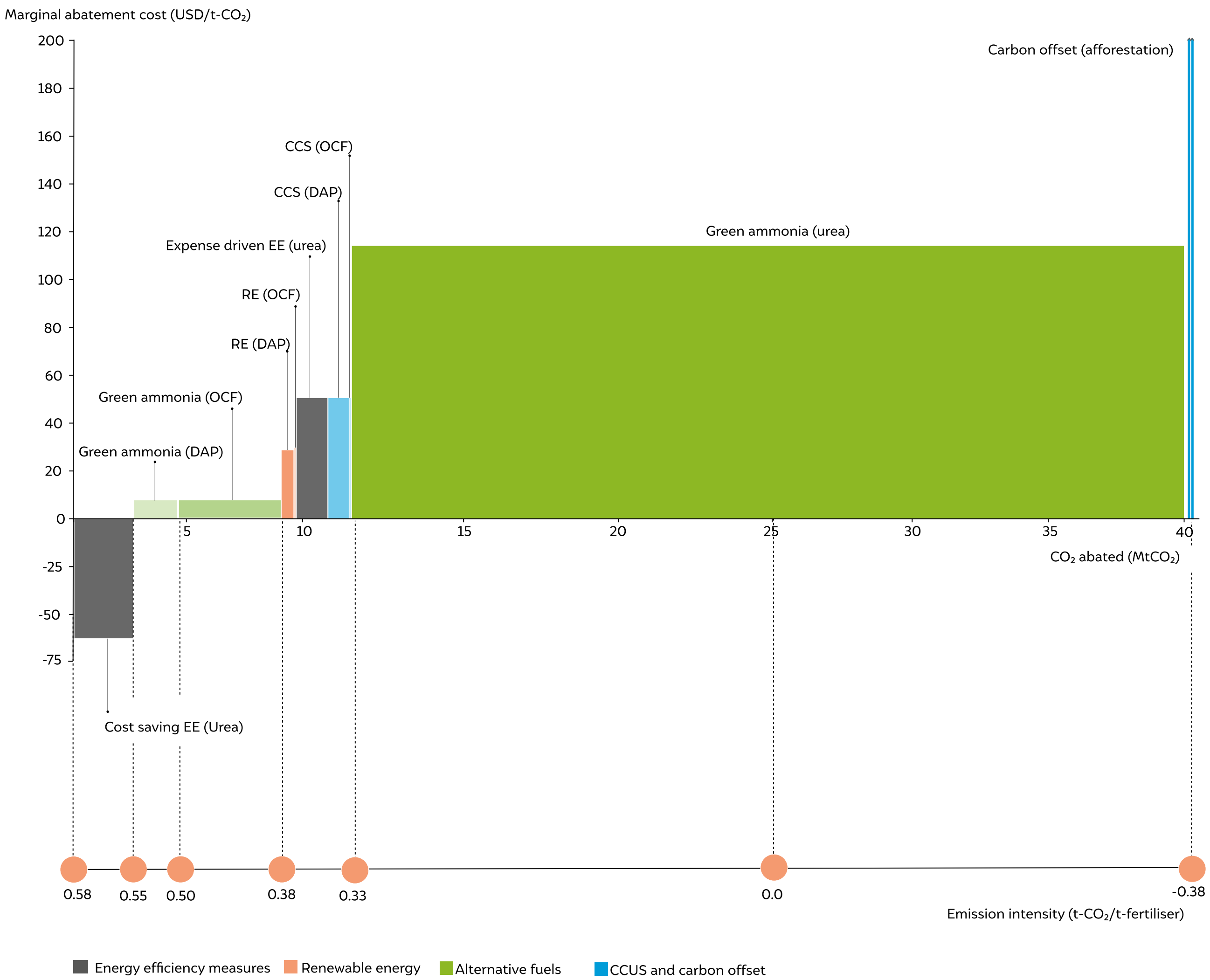
The MAC curve shown in Figure 14 captures the impact of the higher prices of fossil fuels. Compared to the base case where the MAC with green ammonia was USD 270 per t-CO2, using green ammonia for urea production at higher gas prices results in an MAC of USD 120 per t-CO2. Additionally, due to increased electricity costs, the abatement cost for switching to RE decreased. Carbon offset, however, remains the most expensive technology.

Table 4 Parameters considered for the sensitivity analysis

Assumptions	Value (base case)	Value (sensitivity case)	Unit
Cost of natural gas (urea)	7.5	11.25	USD/MMBtu
Cost of natural gas (DAP/OCF)	10.11	15	USD/MMBtu
Electricity cost	4.53	5.46	INR/kWh
Cost of grey ammonia (urea)	278	392	USD/t
Cost of grey ammonia (DAP/OCF)	357	511	USD/t
Cost of green ammonia	700	525	USD/t
CCS cost	90	50	USD/t-CO_2

Source: Authors' analysis

Figure 14 Cumulative MAC for the fertiliser sector with sensitivity analysis



Source: Authors' analysis

7. Policy recommendations and conclusion

Based on our analysis, achieving net-zero emissions in the fertiliser industry will require specific policy interventions. The recommendations below outline the critical interventions required.

- **Incentivise the adoption of the best available energy-efficient technologies through the Indian Carbon Market**

  The *Indian Carbon Market* (ICM) and the *Perform, Achieve, and Trade* (PAT) schemes can play a crucial role in encouraging the widespread uptake of EE technologies (Bureau of Energy Efficiency n.d.). EE measures can potentially mitigate ~2.3 MtCO2, which constitutes 10 per cent of emissions from the fertiliser industry. Financial incentives will encourage businesses and industries to adopt EE technologies, leading to operational efficiency and reduced carbon emissions. As we prioritise sustainability, incentivising EE technologies becomes a key driver for realising positive environmental impacts.

- **Incentivise RE uptake in the fertiliser sector**

  By providing financial and policy support, the government can promote the adoption of RE in the fertiliser sector. Governments should also support decarbonisation by waiving or reducing open access charges for renewable power. This approach will help reduce the sector's carbon footprint and will contribute to the overall transition to cleaner and more environmentally friendly production practices.

- **Blend green ammonia in the fertiliser industry**

  Promoting the use of green ammonia can have transformative effects on the fertiliser industry, as ~35 $MtCO_2$ can be abated by switching to green ammonia. Despite cost-related challenges being a barrier to immediate adoption, a gradual and phased approach to adopting green ammonia through blending could be a viable solution. By incrementally increasing the utilisation of green ammonia blends, the industry can strategically transform into a net-zero fertiliser sector.

- **Promote the use of green ammonia for the production of green urea ammonium nitrate and other nitrates**

  Urea ammonium nitrate (UAN) is a popular liquid fertiliser widely used in North America and Europe. It is produced by blending ammonium nitrate with urea. Ammonium nitrate produced from green ammonia can be blended with urea to produce green UAN.

- **Co-locate bioethanol and urea plants**

  CO_2 generated as by-product during the production of bioethanol can be used to produce urea. New bioethanol plants need to be set up to achieve the revised target of blending 20 per cent of bioethanol in petrol by 2025. It is recommended that these new plants be located near urea plants.

India is the second-largest importer of urea with ~10 MT imported in FY2022-23

Image: iStock

Annexure I Parameter and assumption used in the analysis

S.No.	Parameter	Value	Unit	Remark
1	Emission factor of electricity	1.064	kg-CO2/kWh	62% is from captive, 33% from the grid, and 5% from RE (Central Electricity Authority 2020)
2	Emission factor of natural gas	0.27	t-CO_2/GCal	(Gómez and Watterson 2006)
	Calorific value			
3	Natural gas calorific value	52,250	kCal/kg	
4	Hydrogen (LHV)	120	MJ/kg	
5	Ammonia (LHV)	18.8	MJ/kg	
	Conversion factor			
6	1 USD	75	INR	Average for the year 2020
7	1 tonne urea	0.57 0.73	tonne NH_3 tonne CO_2	Based on stoichiometry
8	1 tonne NH_3	0.18 0.82	tonne H_2 tonne N_2	Based on stoichiometry
9	1 GJ	277.78	kWh	
10	1 MMBtu	1.055	GJ	
	Prices			
11	Cost of natural gas (urea)	7.5	USD/MMBtu	Industry experts
12	Cost of natural gas (DAP/OCF)	10.11	USD/MMBtu	Industry experts
13	Electricity cost	4.53	INR/kWh	62% is from captive, 33% from the grid, and 5% from RE (Central Electricity Authority 2020)
14	Cost of grey ammonia (urea)	278	USD/t	Based on natural gas price
15	Cost of grey ammonia (DAP/OCF)	357	USD/t	Based on natural gas price
16	Cost of green ammonia	700	USD/t	Assumed
17	Transport cost of CO_2	15	USD/t	(Smith, et al. 2021)
18	CO2 capture cost	50	USD/t-CO2	(IEA 2019)
	Financial assumptions			
19	Interest rate	10	Percentage	Assumed
20	No. of years	10	Years	Assumed
21	No of payments	120		Assumed

Acronyms

AS	ammonium sulphate
BVFCL	brahmaputra valley fertilizer corporation limited
CAPEX	capital expenditure
CCS	carbon capture and sequestration
CCU	carbon capture and utilisation
CCUS	carbon capture, utilisation, and storage
CPP	captive power plant
DAP	di-ammonium phosphate
EE	energy efficiency
ICM	Indian carbon market
LNG	liquified natural gas
MAC	marginal abatement cost
MAP	mono-ammonium phosphate
MMBtu	million British thermal units
MoP	muriate of potash
$MtCO_2$	million tonnes of CO_2
MTPA	million tonnes per annum
OCF	other complex fertiliser
OPEX	operating expenditure
PSU	public sector undertaking
RE	renewable energy
RTC	round-the-clock
SEC	specific energy consumption
SSP	single super phosphate
TEN	target energy norm
VAR	vapour absorption refrigeration

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