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Carbon-to-Chemicals: A Techno-Commercial Assessment

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Executive Summary

Carbon capture and utilisation (CCU) is an innovative concept that involves converting carbon dioxide (CO_2) captured from point sources of emission or the air into value-added products. It has been gaining considerable attention lately for its role in realising a circular economy. In this context, our study aimed to examine the techno-economics of producing methanol and urea from the captured CO_2, while also evaluating the implications of producing these chemicals domestically, instead of importing them.

Methanol and urea are among the most-used chemicals in Indian industries. In financial year (FY) 2021–22, their consumption was 2.55 million metric tonnes (MMT) and 34.2 MMT, respectively. The domestic production of these chemicals is limited and dependent on fossil fuels (for their synthesis). In 2021–22 alone, 2.4 MMT of methanol and 9.1 MMT of urea were imported, for which India spent INR 7,380 crore and INR 47,170 crore, respectively. The demand for methanol and urea is expected to soar to 4.2 MMT and 53.5 MMT, respectively, by 2030 (Ministry of Road Transport & Highways, 2017).

Delving into the key techno-economic aspects of methanol and urea production from captured CO_2, this study undertakes a comprehensive investigation to evaluate the production technologies, considering raw material requirements, process methodologies, operational parameters, and efficiency metrics. A thorough examination of investment and operating costs—including the calculation of levelised costs— is also undertaken to provide insights into the economic feasibility of the production processes. Further, a nuanced impact analysis is performed to evaluate the potential impact of replacing the traditionally manufactured or imported chemicals with the methanol and urea derived from the captured CO_2. This entailed an examination of the required investment, payback periods, profitability aspects, and the overall economic implications, offering valuable insights into the viability and feasibility of adopting alternative methods for chemicals production.

The study finds that capturing a very small percentage of India's point source emissions (CO_2) could satisfy the raw material needs of these chemicals—0.22% of CO_2 for green methanol and 0.46% of CO_2 for green urea production.

Although the initial investments for establishing and running green methanol and urea plants are high, expanding pilot programmes, scaling up production, increasing the number of carbon capture plants, and reducing CO_2 and hydrogen (H_2) costs can bring about a significant reduction in both investment and operational costs, making the production sustainable. The production of green chemicals using CO_2 also aligns with the goals of *Atmanirbhar Bharat*.

Currently, India's demand for methanol and urea is being met through imports. Since this demand is considerable, it would be challenging to fulfil it domestically through just one or two large-scale green methanol and urea plants. Thus, for a realistic implementation of the carbon-to-chemicals approach, it is assumed that 15 methanol plants and 58 urea plants will be required to meet India's import demand. The economic impact analysis performed under this study encompasses factors such as potential investments, profitability, cost savings from avoided imports, and potential carbon repurposing.

Key Insights

The key insights from this study illustrate how the green methanol and green urea production process (that utilises the captured CO_2) can foster sustainable domestic production of these chemicals and avoid the need to import them. They, thus, make a business case for producing green methanol and green urea domestically.

Green Methanol	Green Urea
Investment Required	
A capital expenditure (CapEx) of INR 10,700 crore and an operating expenditure (OpEx) of INR 24,000 crore/year.	A CapEx of INR 55,200 crore and an OpEx of INR 55,400 crore/year.
Payback Periods	
Payback periods for green methanol plants have seen a variation of 4–14 years (with a selling price of INR 103–110 per kg).	Payback periods for green urea plants have seen a variation of 4–14 years (with a selling price of INR 65–75 per kg).
Import Expenses	
Avoided direct import expenses amount to INR 1.85 lakh crore over a lifetime of 25 years.	Avoided direct import expenses amount to INR 11.8 lakh crore over a lifetime of 25 years.
Monetary Savings	
Opting for investment (both CapEx and OpEx) in green methanol can lead to substantial net monetary savings (of INR 1.92 lakh crore over 25 years), attributable to the avoidance of imports.	Opting for investment (both CapEx and OpEx) in green urea can lead to substantial net monetary savings (of INR 12.23 lakh crore over 25 years), attributable to the avoidance of imports.
Carbon Utilisation Potential	
This approach repurposes 3.57 MMT of CO_2 to produce 2.4 MMT of methanol.	This approach repurposes 7.47 MMT of CO_2 to produce 9.1 MMT of urea.

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Abbreviations

ASU	Air Separation Unit
BCM	Billion Cubic Metres
BOP	Balance of Plant
CapEx	Capital Expenditure
CH_3OH	Methanol
CO	Carbon monoxide
CO_2	Carbon dioxide
FY	Financial Year
Gt	Giga tonne
H_2	Hydrogen
H_2O	Water
IEAGHG	International Energy Agency Greenhouse Gas
INR	Indian Rupee
IRR	Internal Rate of Return
Kg	Kilogram
LCOM	Levelised Cost of Methanol
LCOU	Levelised Cost of Urea
MMT	Million Metric Tonne
MMTPA	Million Metric Tonne Per Annum
MT	Metric Tonne
MTPD	Metric Tonne Per Day
NG	Natural Gas
NH_2CONH_2	Urea
NH_3	Ammonia
NH_4COONH_2	Ammonium carbamate
OpEx	Operating Expenditure
PFD	Process Flow Diagram
PFR	Plug Flow Reactor
PPM	Parts Per Million
RE	Renewable Energy
RWGS	Reverse Water Gas Shift
Tpd	Tonne per day
Tph	Tonne per hour
TRL	Technology Readiness Level

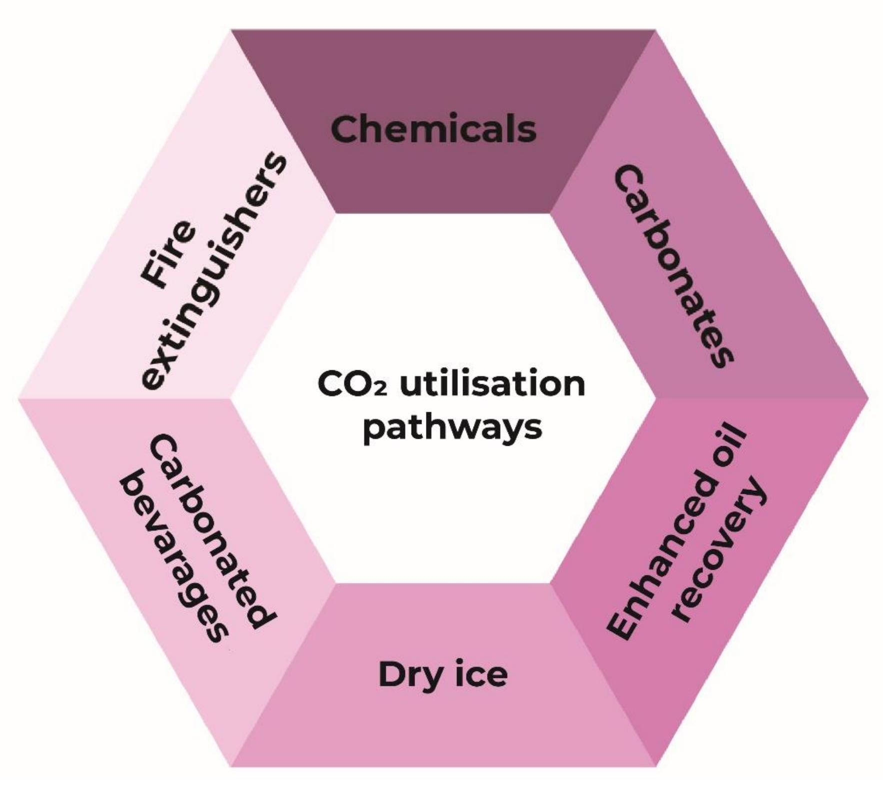
1. Introduction

India relies heavily on fossil fuels—with approximately 80% sourced from coal, oil and gas, and biomass—to meet its energy demand that comes primarily from sectors like power, transportation, construction, and the chemical industry. Despite energy efficiency (EE) measures and contributions from renewable energy (RE) sources, the reliance on fossil fuels persists to meet the escalating energy demand. In 2019, India's carbon emissions reached 2.9 giga tonnes (Gt) (McKinsey Sustainability, 2022), and projections indicate a potential increase to 3.8–3.9 Gt by 2030 (Carbon Brief, 2018).

Mitigating climate change entails stabilising greenhouse gas concentrations between 445 and 490 parts per million (ppm) to prevent a 2 °C temperature rise (European Environment Agency, 2016). Thus, to achieve its ambitious net-zero target by 2050, India needs a comprehensive approach that not only involves integrating RE and EE improvements, but also explores alternative technologies to curb emissions. Carbon capture utilisation and storage (CCUS) emerges as a promising option that can contribute significantly to achieving the net-zero goal.

This study focusses on utilising the captured carbon for producing value-added products to improve energy security, reduce imports, and mitigate emissions. Various value-added products can be derived from carbon dioxide (CO_2), as illustrated in Figure 1.

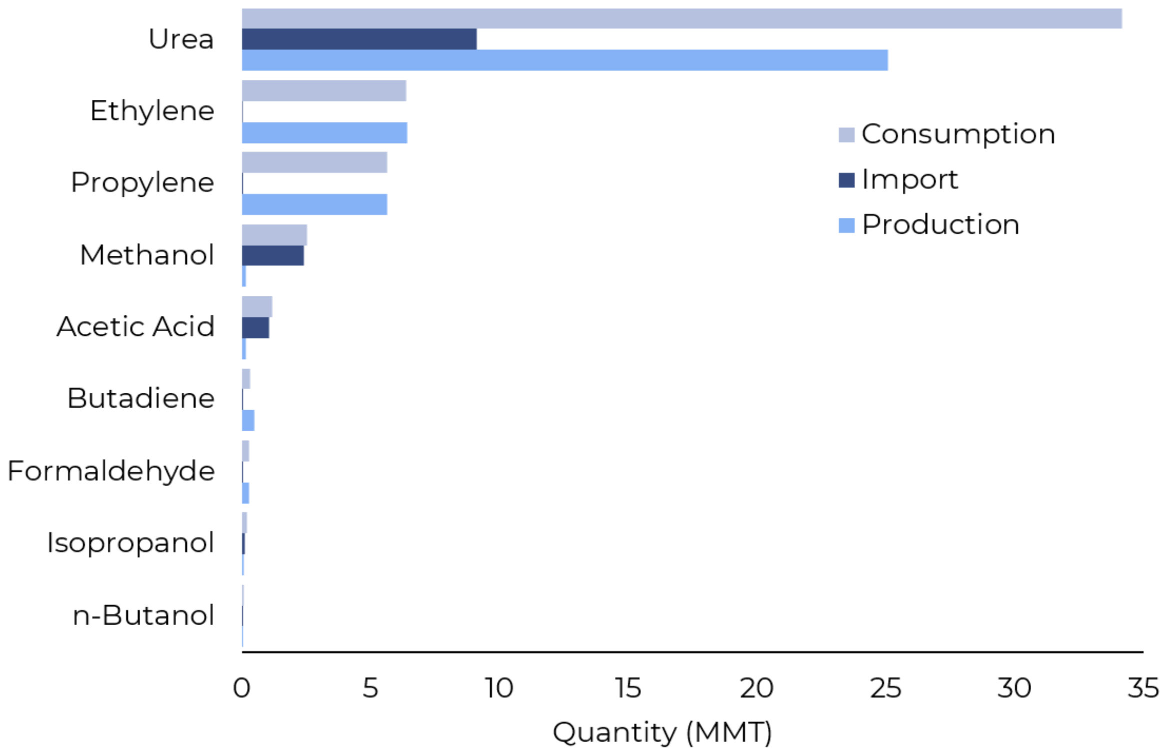
Figure 1: Utilisation of captured CO_2



Given that currently most chemicals are either being manufactured using fossil fuels or being imported from other countries, a change in the trajectory of chemicals production is imperative for India to move towards net zero.

Methanol, ethanol, acetic acid, formaldehyde, urea, isopropanol, n-butanol, ethylene, propylene, butadiene, etc., are some value-added chemicals that can be produced using the captured CO_2. Figure 2 shows the total consumption, import, and domestic production quantities of major chemicals in India in the financial year (FY) 2021–22 (Department of Chemicals and Petrochemicals, 2022; Department of Fertilizers, 2023).

Figure 2: Consumption, import, and production of chemicals in India (FY 2021–22)



India's reliance on the imports of methanol (94% of the total demand is met through imports) and urea (27% of the total demand is met through imports) is heavy, as seen in Figure 2. Eighty-five percent of crude oil used in India—equivalent to 220 MMT—has to be imported to meet the fuel requirements of the transport sector (Ministry of Petroleum and Natural Gas, 2023). Methanol can be used as a fuel or be blended with petrol, without having to make significant modifications to gasoline engines. Further, it is used as a raw material for producing various chemicals (like acetic acid and formaldehyde) and is also being trialled as an alternative marine fuel for blending with petrol. As the domestic production of urea happens through the conventional process, fossil fuels are used extensively. Conventional urea production depends primarily on the availability of natural gas and the country imported 30.78 billion cubic metres (BCM) of natural gas in 2021–22.

The conventional production processes emit 0.5 tCO_{2e}/tonne of methanol and 0.9 tCO_{2e}/tonne of urea (Alsayegh et al., 2019; Pérez-Fortes et al., 2015; Zhang et al., 2021). Urea is majorly used as a fertiliser and is, thus, essential for India's agriculture, as well as for plastic production. The main producers of methanol and urea include the Gujarat Narmada Valley Fertilizers & Chemicals Limited (GNFC) and the Krishak Bharati Cooperative Limited (KRIBHCO), with capacities of 0.16 MMTPA and 1.8 MMTPA, respectively. Yet, in FY 2021–22 alone, India spent INR 7,380 crore and INR 47,170 crore, respectively, on methanol and urea imports.

By 2030, the demand for methanol is expected to rise to 4.2 MMT and that for urea to 53.5 MMT (Ministry of Road Transport & Highways, 2017).

This study focussed on assessing the commercial viability of producing methanol and urea from the captured CO_2 to attend to India's fuel/energy and fertiliser demand. It also evaluated the potential impact of substituting the conventional fuels and chemicals in India with green chemicals.

The report is structured into four main sections. Section 1 introduces the study's background and context, and Section 2 outlines the study's objectives. Section 3 details the methodology and processes employed for the techno-economic analysis of methanol and urea production, along with the corresponding results, while Section 4 examines the economic impact of transitioning from conventional to green production methods.

2. Study Objective

The objective of the study was to evaluate the technical feasibility and commercial viability of producing methanol and urea by utilising captured CO_2, through an in-depth techno-commercial analysis. It also aimed to examine the economic implications of shifting from conventional to green routes for producing these chemicals and avoiding their imports.

Thus, the study attempts to ascertain whether the import costs of methanol and urea can be avoided by producing them domestically via a green route.

3. Methodology

The following components together form the process of the study and reflect its methodology:

1. **Technology Assessment:** Involves the evaluation of methanol and urea production technologies in terms of raw material requirements, process methodologies, operational parameters, efficiency metrics, and other key performance indicators.
2. **Cost Assessment:** Includes the assessment of investment and operating costs and the calculation of levelised costs for production of methanol and urea.
3. **Commercial Prospects**: Relate to investigating the commercial availability of technologies dedicated to produce urea and methanol, with a focus on technology readiness levels (TRLs).
4. **Impact Analysis:** Involves assessing the potential impact of substituting the traditionally produced and/or imported chemicals with those produced through the green route, in terms of required investments and associated payback periods, providing insights on the economic implications of adopting these alternative chemical production methods.

3.1. Study Assumptions

The following assumptions and considerations have been made for this study:

1. The terms 'green methanol' and 'green urea' refer to the methanol and urea produced from captured CO_2 and hydrogen (H_2) generated from an electrolyser using renewable energy sources.
2. Raw material costs have been considered as follows: CO_2: INR 3.4 to 10 per kg; Green H_2: INR 250 to 410 per kg.
3. For estimating levelised cost, a range of discount rates—from 5% to 20%—has been considered.
4. An operation and maintenance escalation rate of 2% has been assumed.
5. Cost escalation for imports has not been accounted for while estimating net monetary benefits.
6. Carbon capture costs have been considered as INR 0.3 to 1.0 crore per metric tonne per day (MTPD).
7. The capital expenditure (CapEx) of transporting CO_2 is assumed to be 5–15% of the total CapEx of carbon capture and manufacturing plant.
8. The operating expenditure (OpEx) for carbon capture and transportation has been considered as 20% and 0.4% of the respective CapEx.
9. The economic analysis of methanol and urea production considers sourcing raw materials (H_2 and CO_2) externally.
10. Human resource costs are assumed to be 2–4% of the total operation and maintenance (O&M) costs.
11. The internal rate of return (IRR) estimation considers a constant cash inflow.
12. The economic impacts come from a preliminary analysis that does not account for loan-related factors.
13. The Indian rupee has been converted into the US dollar using the exchange rate as of 2 May 2024 (viz., 1 USD = INR 83.46).
14. It has been assumed that the total domestic production for meeting India's import demand is handled by 15 methanol plants and 58 urea plants.
15. Lang factor considers the following cost share of different components in an equipment, besides direct and indirect costs (for estimating the total CapEx for plants with higher capacities):

Table 1: Cost share of different components

Components	Fraction of equipment cost
Piping	70%
Instrumentation	20%
Electrical system	10%
Process building	15%
Utilities	50%
Storages	15%
Site preparation	5%
Auxiliary building	15%
Erection	45%
Design and engineering	30%
Contractor’s fee	5%
Contingencies	10%

4. Techno-Economic Assessment

Under the techno-economic assessment, the production of methanol and urea through conventional methods was compared with processes that use captured CO_2 to produce them. It involved examining the variations in process configurations and technical parameters like raw materials, conversion efficiencies, and energy consumption. The investment and operational costs have been evaluated and the levelised costs have also been estimated. The assessment provides insights into the technical feasibility and commercial viability of green technologies.

4.1. Technology Assessment for Methanol

This section presents the assessment of traditional and CO_2-based technologies for producing methanol. The process flow diagram (PFD) serves as the basis for assessing the technology.

4.1.1. Traditional Methanol Production

Figure 3 shows the PFD of a traditional methanol plant with a capacity of **0.1 tph**. The plant employs coal, biomass, or natural gas as feedstock, utilising either gasification or reforming processes to generate syngas. This H_2 to CO molar ratio for syngas is ensured at 2:1 for methanol production. To produce 1 kg of methanol, **0.88 kg of CO** and **0.13 kg of H_2** are required. The methanol synthesis reactor operates within a temperature range of **200–320°C** and a pressure range of **40–120 bar**, facilitated by a suitable catalyst (Cu/Zn/Al_2O_3) (De María et al., 2013). The following reaction takes place in the methanol synthesis reactor:

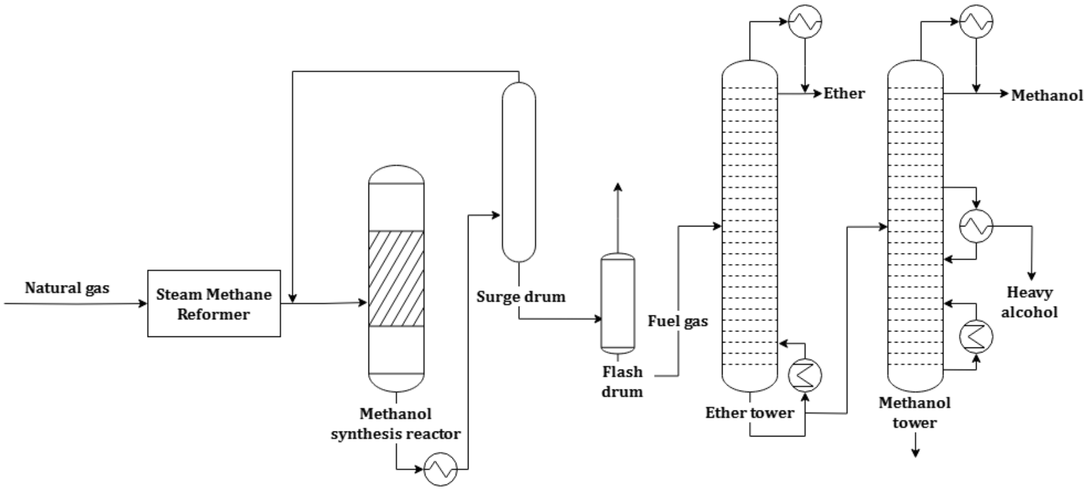
Methanol synthesis

$$CO + 2H_2 \rightarrow CH_3OH \qquad \text{(R 1)}$$

The surge drum separates water from the reaction product while recycling trace amounts of unreacted H_2 and CO. The unwanted gases are efficiently removed through a flash drum, and aldehydes and ketones are eliminated by a rotary drum. To achieve the highest purity, the methanol stream undergoes a final purification process in which ether and higher alcohols are removed using a two-stage distillation column.

Overall, a traditional plant achieves a ***feed-to-product conversion of 63%*** *and requires* ***0.88 kg CO/kg methanol*** *and* ***0.13 kg H_2/kg methanol.***

Figure 3: Conventional methanol production



4.1.2. Hydrogenation Route for Methanol Production

The process through which methanol is produced using captured CO_2 is referred to as the 'hydrogenation process'. The study considered the PFDs published by DWSIM—an open-source chemical process simulator tool—as the reference point for the assessment of two hydrogenation processes: **Route 1** (plant capacity of **0.15 tph**) and **Route 2** (plant capacity of **60 tph).**

4.1.2.1. DWSIM Route 1: Plant Capacity of 0.15 tph

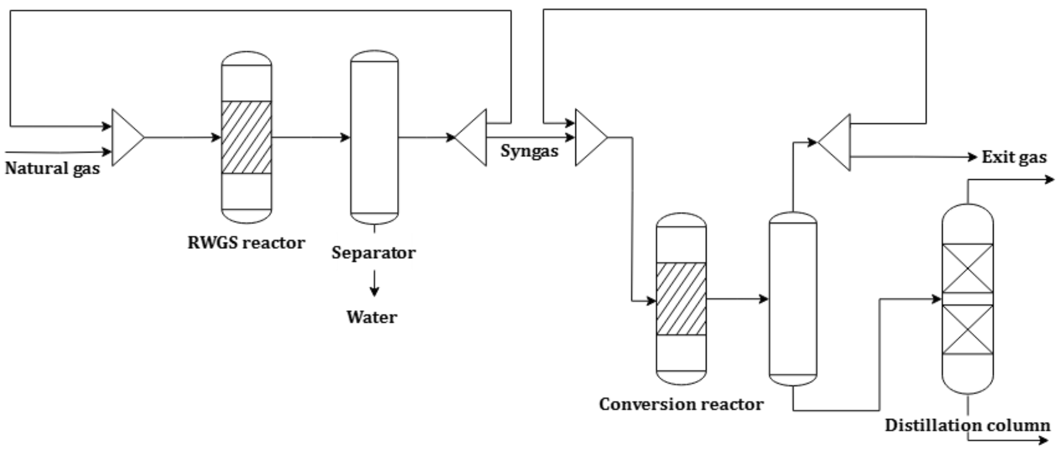
This method, referred to as the **CAMERE process** (carbon dioxide hydrogenation to form methanol via a reverse-water-gas-shift reaction), involves a two-step hydrogenation process to produce methanol: step 1) a reverse-water-gas-shift (RWGS) reaction; and step 2) chemical synthesis.

Figure 4 shows the PFD of the CAMERE process (Sutariya, 2020). Here, H_2 and CO_2 serve as feedstocks with a molar ratio of 3.37:1 and are introduced into the RWGS reactor operating at 500°C and 10 bar to generate water gas (CO and H_2O). This water gas subsequently reacts with H_2 to produce methanol (CH_3OH). As a catalyst, the individual or compounded chemicals of Cu, Zn, or Al_2O_3 are used (the conventional process of methanol production also uses the same catalyst). The following reactions occur in this process:

$$CO_2 + H_2 \leftrightarrow CO + H_2O \qquad \text{(R 2)}$$

$$CO + 2H_2 \rightarrow CH_3OH \qquad \text{(R 3)}$$

Figure 4: Methanol production through CO_2 hydrogenation (CAMERE process)



Flash drum 1 removes water formed in the RWGS reactor and allows pure CO participation (at 2.5°C and 8 bar) in the chemical synthesis to produce methanol. The conversion efficiency of RWGS is 60%. Subsequently, recycle block 1 recycles 40% of the reactor's product stream back into the feed mixer. The remaining syngas undergoes compression (8 bar) and produces methanol (with chemical synthesis reactor operating at 250°C). Then, flash drum 2 removes the unreacted gases (CO, CO_2 and H_2) from the exit stream (at 11.85°C and 7.5 bar) and recycle block 2 recycles the unreacted CO for further participation in chemical synthesis. Finally, the distillation column (at 11.85°C and 7.54 bar) separates water and provides purified methanol (with a concentration of 97.4%).

Overall, a two-step hydrogenation plant achieves a ***feed-to-product conversion of 64%*** *and requires* ***2.45 kg CO_2/kg methanol*** *and* ***0.4 kg H_2/kg methanol.***

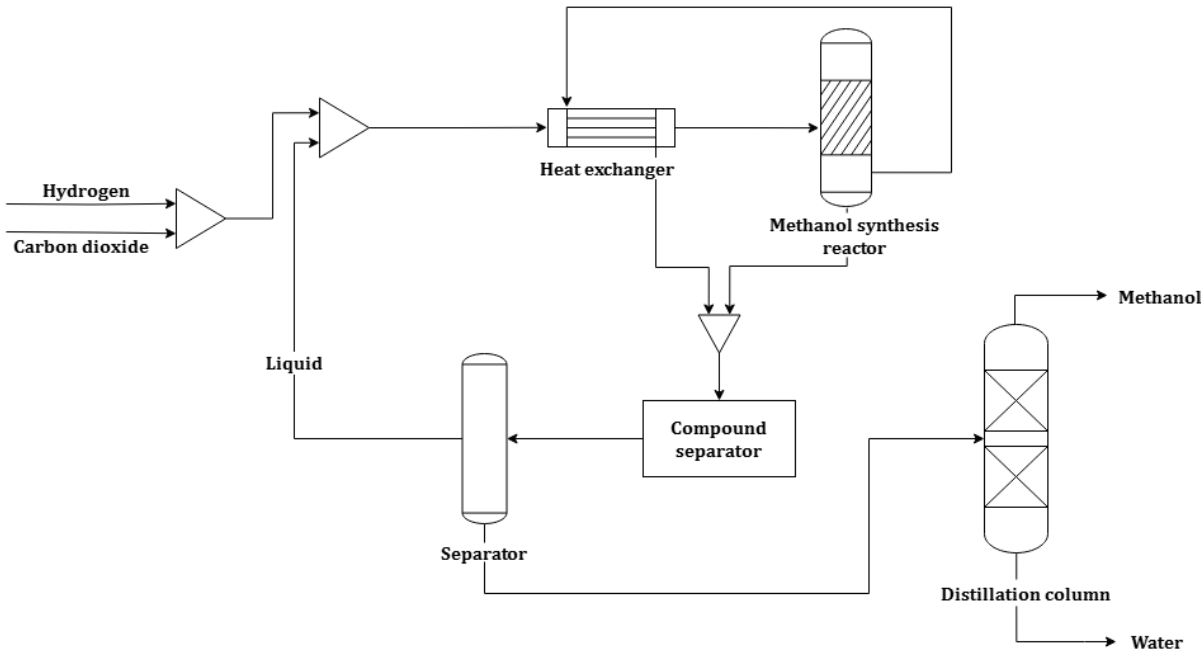
4.1.2.2. DWSIM Route 2: Plant Capacity of 60 tph

This method entails a **single-step hydrogenation process** to produce methanol (avoids RWGS reactor).

Figure 5 presents the PFD of this hydrogenation process (Parra Lara, 2021). Here, H_2 and CO_2 serve as feedstocks with a molar ratio of 3.03:1 and are pressurised to 77.7 bar. The temperature of the feed is increased to 210°C via a heat exchanger before it is passed into an adiabatic plug-flow reactor (PFR), where it undergoes synthesis in the presence of Cu/Zn/Al_2O_3. The following reaction takes place:

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \qquad \text{(R 4)}$$

Figure 5: Direct hydrogenation of CO_2



Recycle block 1 helps in recycling the unreacted stream (CO_2 and H_2) from the reactor and extracts the heat to meet the temperature required (via a mixed-flow heat exchanger) for the main feed prior to chemical synthesis. The unreacted gases of the reaction product are removed in a flash drum operating at normal temperature and pressure (NTP).

Finally, recycle block 2 recovers 99% of the unreacted gases from the product stream and methanol is purified via the distillation column (at 79°C and 1.1 bar).

Overall, a single-step hydrogenation plant achieves a ***feed-to-product conversion of 59%*** *and requires* ***1.48 kg CO_2/kg methanol*** *and* ***0.2 kg H_2/kg methanol.***

4.1.2.3. Comparison: Route 1 and Route 2

Route 1 and Route 2 can be compared with regard to the following features:

- **Plant capacity**: Route 1 produces methanol with a plant capacity of 0.15 tph while Route 2 produces methanol with a plant capacity of 60 tph.
- **Catalyst**: Both routes employ a similar catalyst ($Cu/Zn/Al_2O_3$).
- **Equipment**: Route 2 uses more equipment (heaters, coolers, compressors, etc.), mainly due to increased plant capacity (see Appendix).
- **Conversion efficiency:** Route 1 has an efficiency of 64% while Route 2 has an efficiency of 59%.
- **Raw material requirement:** Route 1 uses 2.45 kg of CO_2 to produce 1 kg of methanol while Route 2 uses 1.48 kg of CO_2 to produce 1 kg of methanol. Similarly, Route 1 uses 0.4 kg of H_2 per kg of methanol production while Route 2 uses 0.2 kg of H_2 per kg of methanol production. This also indicates that higher plant capacities can reduce raw material requirements.

4.2. Technology Assessment for Urea

As was done for methanol production, a technology assessment of the traditional and CO_2-based technologies for producing urea has been performed. In this case, the key difference between traditional and CO_2-based technologies relates to the source of raw materials. In the **traditional route**, CO_2 and H_2 are typically sourced through natural gas (NG) reforming, coal gasification, biomass gasification, etc. In the **CO_2-based route,** CO_2 and ammonia (NH_3) are sourced through flue gas captured from fossil-fuel-based plants. For producing urea through this route, RE sources (called green raw materials) are used.

4.2.1. Urea Production Process

Urea production has various well-established processes that include Stamicarbon, Snamprogetti, Chao, and Uchino. Among these, **Stamicarbon** is widely followed for urea synthesis as it has a higher conversion efficiency and is a low-cost option (Meessen & van Baal, 2003).

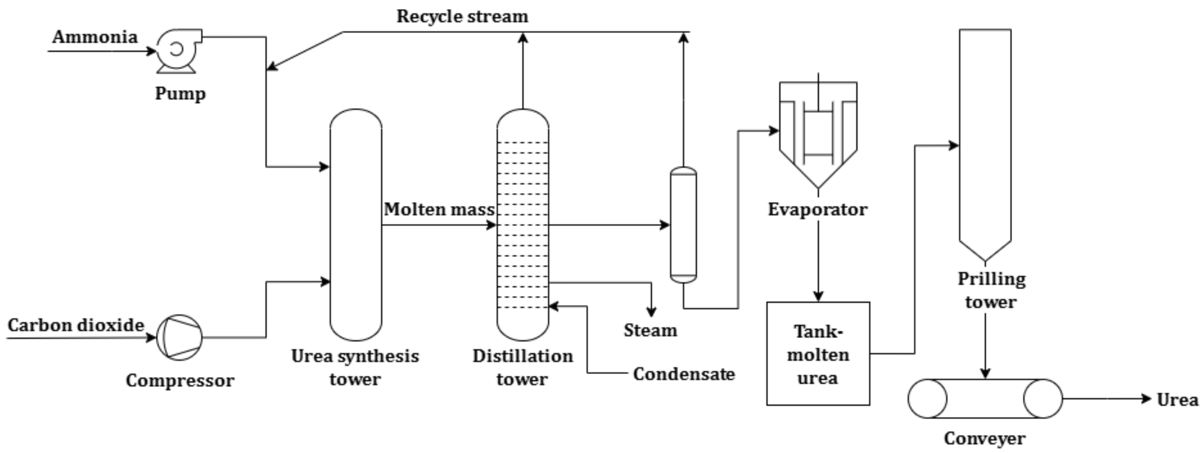
4.2.1.1. Stamicarbon Approach

Figure 6 presents the PFD of urea production using the Stamicarbon CO_2 stripping process. Here, NH_3 and CO_2 are the key raw materials, which are compressed to a pressure of 120 bar. The **chemical synthesis of liquid urea** (170–190°C) happens with two sequential reactions: 1) formation of ammonium carbamate; and 2) dehydration of ammonium carbamate, as shown below:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \quad \text{(R 5)}$$

$$NH_2COONH_4 \rightarrow NH_2CONH_2 + H_2O \quad \text{(R 6)}$$

Figure 6: Stamicarbon CO_2 stripping process



The product stream from the chemical synthesis is considered as **molten mass** (melted urea with water vapour at a temperature of 135°C). The water from the molten mass is separated via the distillation tower and the unreacted stream (CO_2, NH_3, and NH_4COONH_2) is recycled and sent back to the synthesis reactor. The targeted stream from the flash drum (liquid urea) undergoes evaporation to avoid biuret formation and get the concentrated molten urea. The prilling tower facilitates the required cooling of this molten urea to produce granular urea (at room temperature).

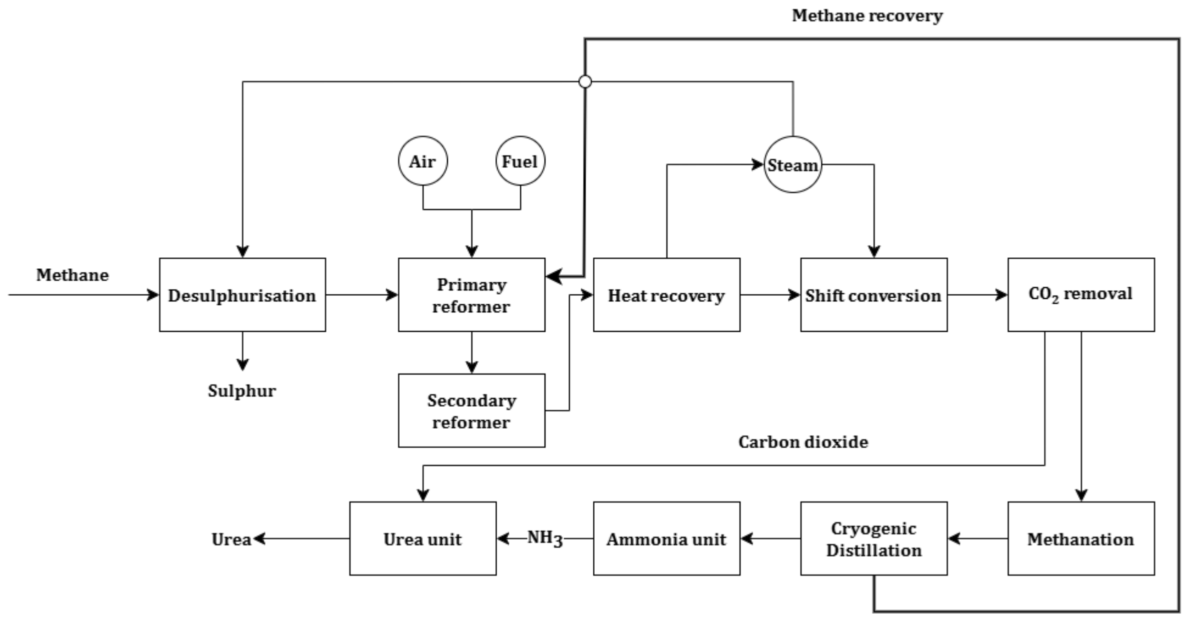
In the following sub-sections, two different pathways for producing urea are described. Both follow the Stamicarbon process for urea synthesis but utilise different sources of raw materials.

*Overall, a Stamicarbon-based urea production plant achieves a **feed-to-product conversion of 77%** and requires **0.82 kg CO_2/kg urea** and **0.1 kg H_2/kg urea.***

4.2.1.2. Conventional Urea Production

Figure 7 describes the conventional route for producing urea. An auto-thermal reformer (ATR) is used for reforming NG, and air acts as a gasifying agent. Post reforming, the petroleum mixture consisting of hydrocarbons undergoes olefin cracking and water gas shift (WGS). The syngas obtained from WGS undergoes the CO_2 removal process. In the methanation unit, all oxygen-containing compounds (water, a small fraction of CO_2, and CO) are removed as they are toxic for NH_3 synthesis. The resultant NH_3 is sent into a urea-synthesis reactor, along with CO_2. The urea thus produced is then directed to a prilling tower, where it is transformed into granules.

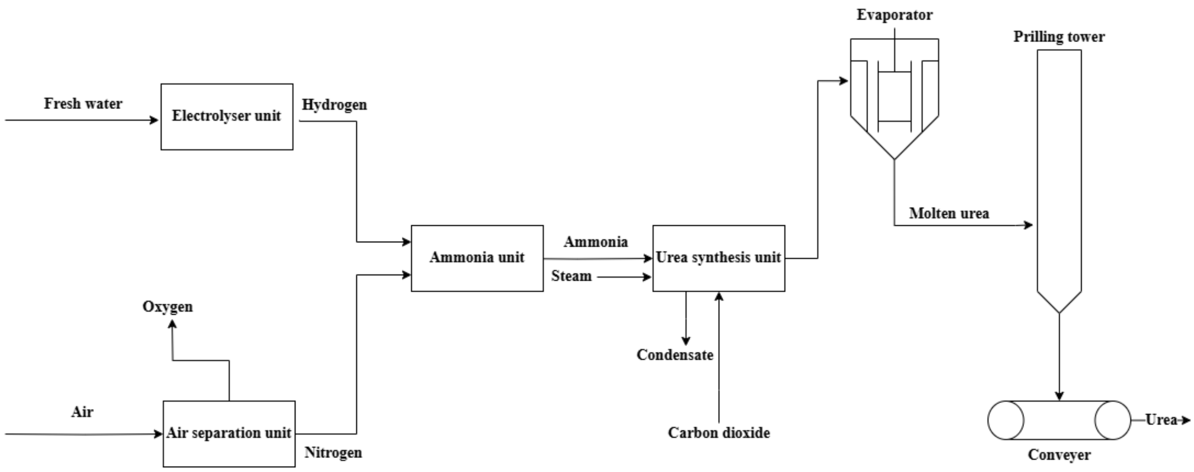
Figure 7: Conventional urea production



4.2.1.3. Green Urea Production

Figure 8 describes the green route for producing urea. In this process, N_2 and H_2 are produced at the outset to synthesise NH_3. An air separation unit (ASU) is used to obtain N_2, while H_2 is obtained through the electrolysis of fresh water. Both are supplied to an ammonia synthesis unit to obtain NH_3. These, along with CO_2, are supplied to a urea synthesis unit to produce urea through the Stamicarbon process. The study assumes that CO_2 is captured from point sources of fossil-fuel-based industries.

Figure 8: Green urea production



4.2.1.4. Comparison: Conventional vs CO_2-based approaches

The traditional and CO_2-based production approaches can be compared with regard to the following attributes:

- **Plant capacity:** The conventional approach has a capacity of 94.2 tph while the CO_2-based or green approach has a capacity of 57.5 tph.
- **Catalyst:** Both approaches employ similar catalysts.

- **Equipment:** The number of units (gasification, water gas shift, CO_2 capture, and methanation) is more in the conventional approach (see Appendix), mainly due to the difference in process path.
- **Conversion efficiency:** Since the ratio of feed (with NH_3 and CO_2 as the feedstock) remains the same, the urea production processes under both approaches have the same conversion efficiency of 77%. Inclusion of N_2, H_2 and CO_2 as feedstock under the green approach leads to a conversion efficiency of 72%.

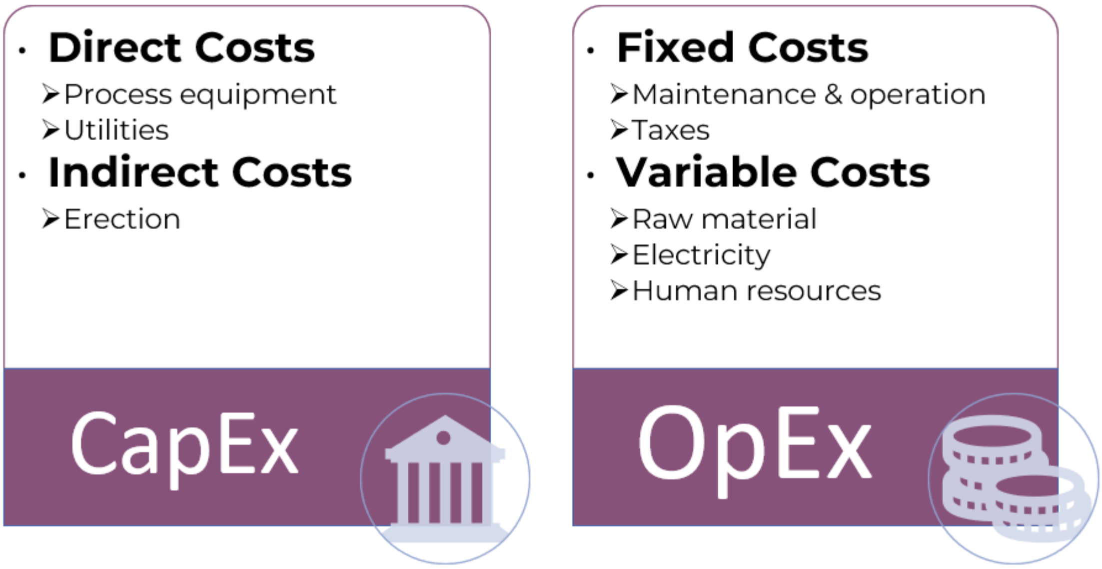
4.3. Economic Assessment

An economic assessment was also conducted under the study to analyse the capital expenditure (CapEx), operational expenditure (OpEx), and levelised costs for producing green methanol and green urea utilising captured CO_2.

4.3.1. CapEx and OpEx

Figure 9 presents the key components of CapEx and OpEx. While CapEx includes one-time investment expenses, such as those on process equipment, technology, buildings, etc., OpEx includes day-to-day expenditures on raw materials and utilities, taxes, wages, etc. The study has considered the published cost data (on CapEx and OpEx) from DWSIM and other literature sources for analysis. Further, a comparison has been made between traditional methods and CO_2-based approaches, which provides insights into the feasibility, viability, and directions for producing these chemicals from captured CO_2.

Figure 9: CapEx and OpEx constituents



4.3.1.1. CapEx and OpEx for Methanol Production

Table 2 provides the detailed CapEx and OpEx for producing methanol through the hydrogenation and the conventional routes. The CapEx and OpEx figures for Route 1 and Route 2 were obtained through the Capital Cost Estimator tool on DWSIM. Kim et al., 2011 was taken as an additional reference for the single-step hydrogenation process and has been included in the table as Route 3. For the conventional methanol production process, plant data from International Energy Agency Greenhouse Gas (IEAGHG) website for the year 2017 was taken as an example. From the table, it is evident that low-capacity hydrogenation plants entail a higher CapEx. Conversely, high-capacity plants have a lower CapEx. Literature review of published cost data (see Appendix) indicates variations in CapEx in the different hydrogenation routes, ranging from -40% to +25%.

Table 2: CapEx and OpEx for green and conventional methanol production

Particulars	Green Process			Conventional Process
	DWSIM: Route 1	**DWSIM: Route 2**	**Route 3** (as mentioned by Kim et al., 2011)	**Approach** (as outlined in IEAGHG, 2017)
Plant capacity (tph)	0.15	60	10	208
CapEx (INR crore)	61	984	190	9,634
OpEx (INR crore/year)	17	3,561	843	4,660

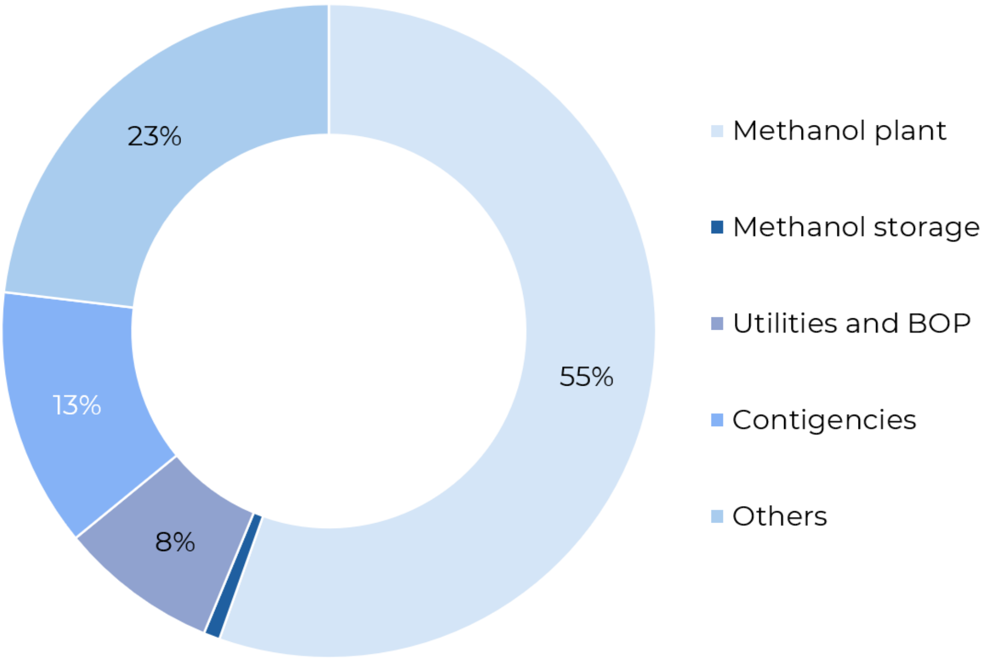
The OpEx component broadly encompasses expenses on raw materials (CO_2 and H_2) and electricity in the hydrogenation case. Table 3 presents a detailed breakup of OpEx for producing 1 kg of methanol. For this analysis, the study considered the cost of captured CO_2 from fossil-fuel-based plants (International Energy Agency, 2020) and the cost of green H_2 produced through the electrolyser route using RE (India-Briefing, 2023). Conventional methanol production uses natural gas (costing INR 39 per kg) as feedstock.

Table 3: OpEx components for methanol production

Components of OpEx	**DWSIM: Route 1**	**DWSIM: Route 2**	**Route 3,** (as mentioned by Kim et al., 2011)	**Reference cost**
CO_2 (kg/kg product)	2.45	1.48	1.84	INR 3.4–10 per kg (USD 0.04–0.12 per kg)
H_2 (kg/kg product)	0.40	0.20	1.18	INR 250–410 per kg (USD 3.6–4.8 per kg)
Electricity (kWh/kg product)	1.06	1.14	2.86	INR 3.7 per kWh (USD 0.04 per kWh)

Figure 10 and Figure 11 show the CapEx and OpEx breakups for the conventional methanol production process. It is observed that the methanol plant equipment forms the largest share of total CapEx (55.43%). Indirect costs, such as design and engineering, along with contractor's fee, have the second-largest share in total CapEx (23.10%). Utilities and balance of plants (BOP) account for nearly 8% of the total investment.

Figure 10: CapEx breakup of conventional methanol production



Within the OpEx, feedstock has the largest share (90%), while maintenance has the second-largest share (4%).

Figure 11: OpEx breakup for conventional methanol production

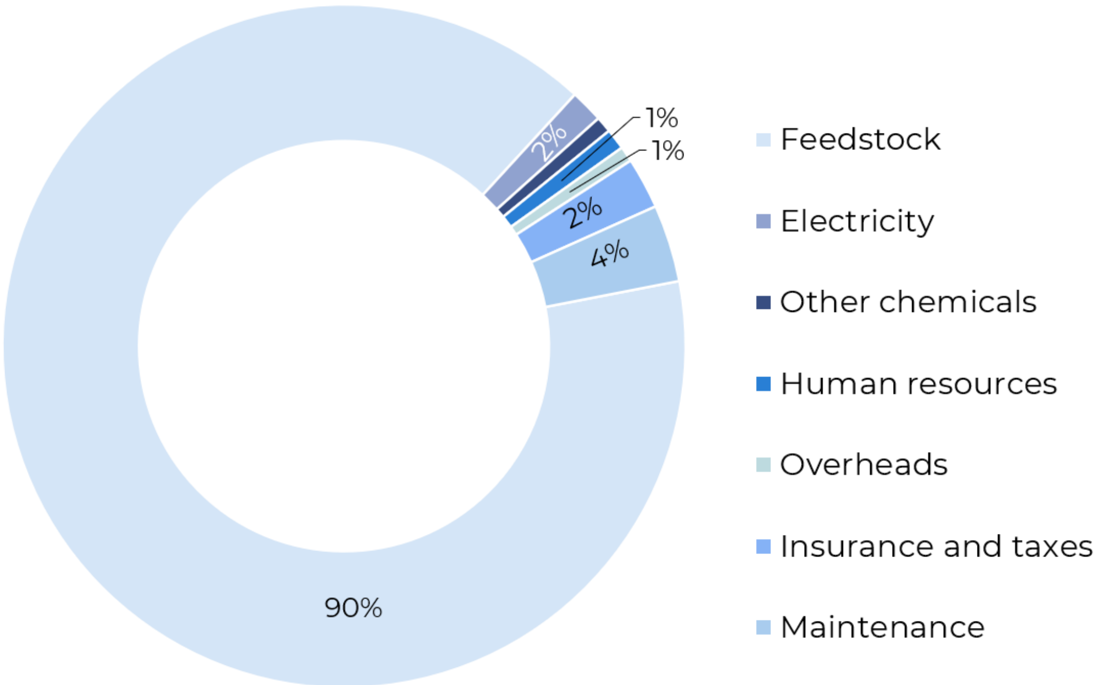
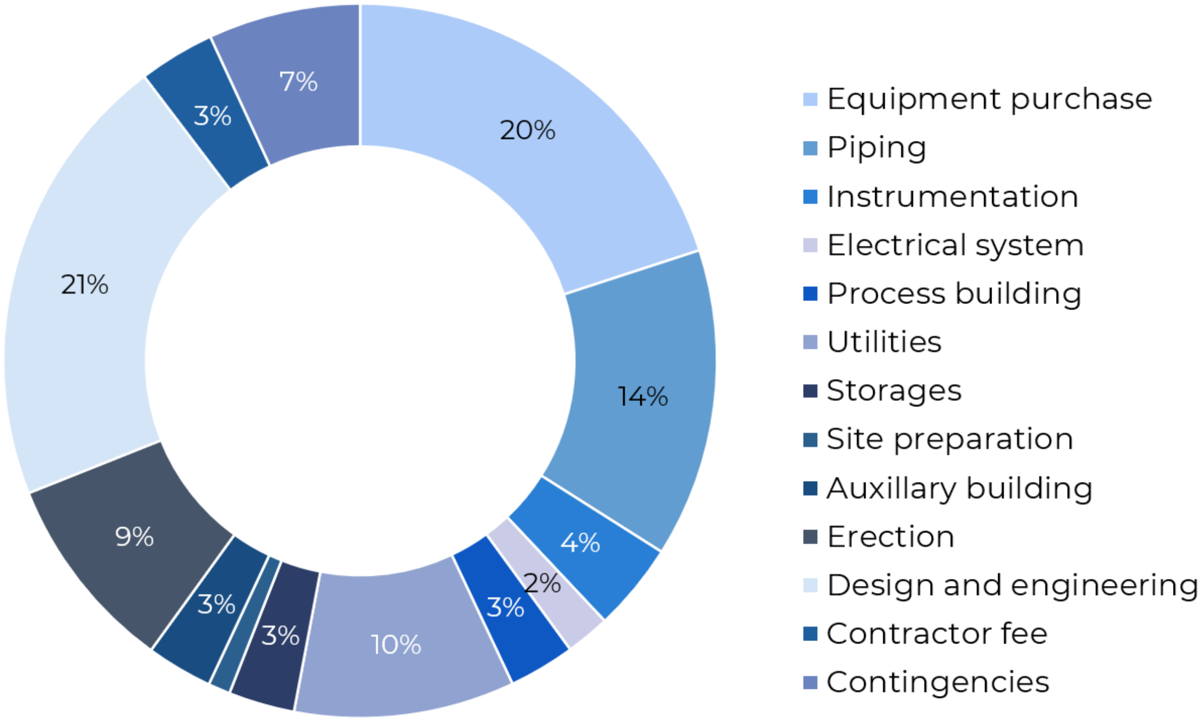


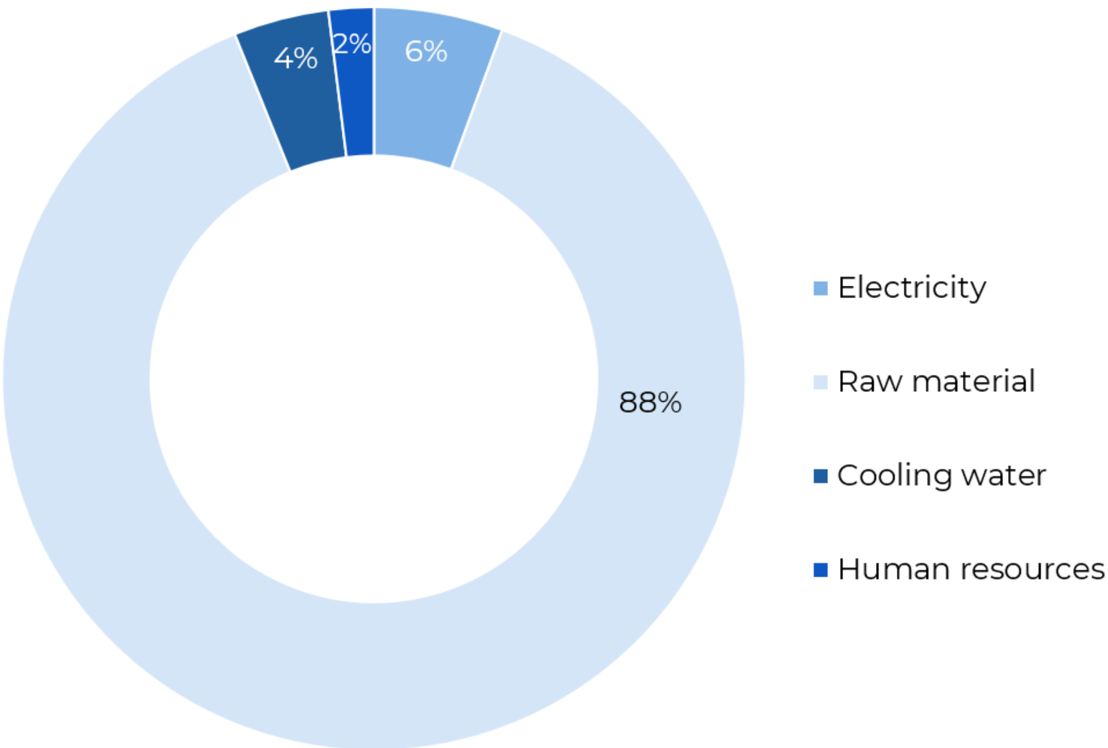
Figure 12 and Figure 13, respectively, show the CapEx and OpEx breakups for the CO2-based methanol production. It is observed that process equipment forms the largest component of total CapEx (20%), followed by piping (14%).

Figure 12: CapEx breakup for CO_2-based methanol production



The CapEx for processes in DWSIM routes 1 and 2 are calculated using Lang factor [1], and hence they remain the same for both. Raw materials constitute the largest part of OpEx (88%).

Figure 13: OpEx breakup for CO_2-based methanol production



[1] Lang factor helps in estimating the total systemic cost; for instance, the lang factor for piping is 70% and the total system cost equals (1+70%) of equipment cost.

4.3.1.2. CapEx and OpEx of Urea Production

Unlike methanol production, most urea production processes follow a single route. For comparing the conventional and green urea production routes, a plant reference from IEAGHG, 2017 was taken as an example (for conventional urea production), and calculations from Khan et al., 2024 were considered (for green urea production). Table 4 provides the CapEx and OpEx for urea production plants. The OpEx of green urea production and conventional urea production vary, primarily due to the difference in their raw material sources.

Table 4: CapEx and OpEx for green and conventional urea production

Particulars	**Green Urea Approach** (as mentioned by Khan et al., 2024)	**Conventional Urea Approach** (as given in IEAGHG, 2017)
Plant capacity (tph)	58	94
CapEx (INR crore)	1,440	7,600
OpEx (INR crore/year)	2,100	1,540

In the case of green urea, the OpEx broadly includes expenditure on CO_2 and electricity.

Table 5 presents the components required for producing 1 kg of urea, along with the reference costs. The cost of CO_2 captured from fossil-fuel-based plants was taken as INR 3.4–10 per kg. Freshwater cost was taken as INR 0.165 per kg (Maharashtra Water Resources Regulatory Authority, 2022), electricity cost as INR 3.7 per kWh (Central Electricity Authority, 2022), NG cost as INR 39 per kg (Petroleum Planning and Analysis Cell, 2024).

Table 5: OpEx components for urea production

Stamicarbon Process			**Reference Cost**
OpEx Components	**Green approach,** (as mentioned by Khan et al., 2024)	**Conventional approach** (as outlined by IEAGHG, 2017)	
NG (kg/kg product)	-	0.39	INR 39 per kg (USD 9.87/MMBTU)
CO_2 (kg/kg product)	0.82	-	INR 3.4-10/kg (USD 0.04-0.12/kg)
Freshwater (kg/kg product)	0.98	-	INR 0.165/kg (USD 0.002/kg)
Electricity (kWh/kg product)	11.30	0.094	INR 3.7kWh (USD 0.04/kWh)

Figure 14 and Figure 15 show the CapEx and OpEx breakups, respectively, for the conventional urea production process. An ammonia and urea plant has a 58.05% share in the total CapEx as it performs NG reforming (to NH_3) and has multiple supporting units for producing urea. Within the OpEx, feedstock and electricity account for the highest share.

Figure 14: CapEx breakup for conventional urea production

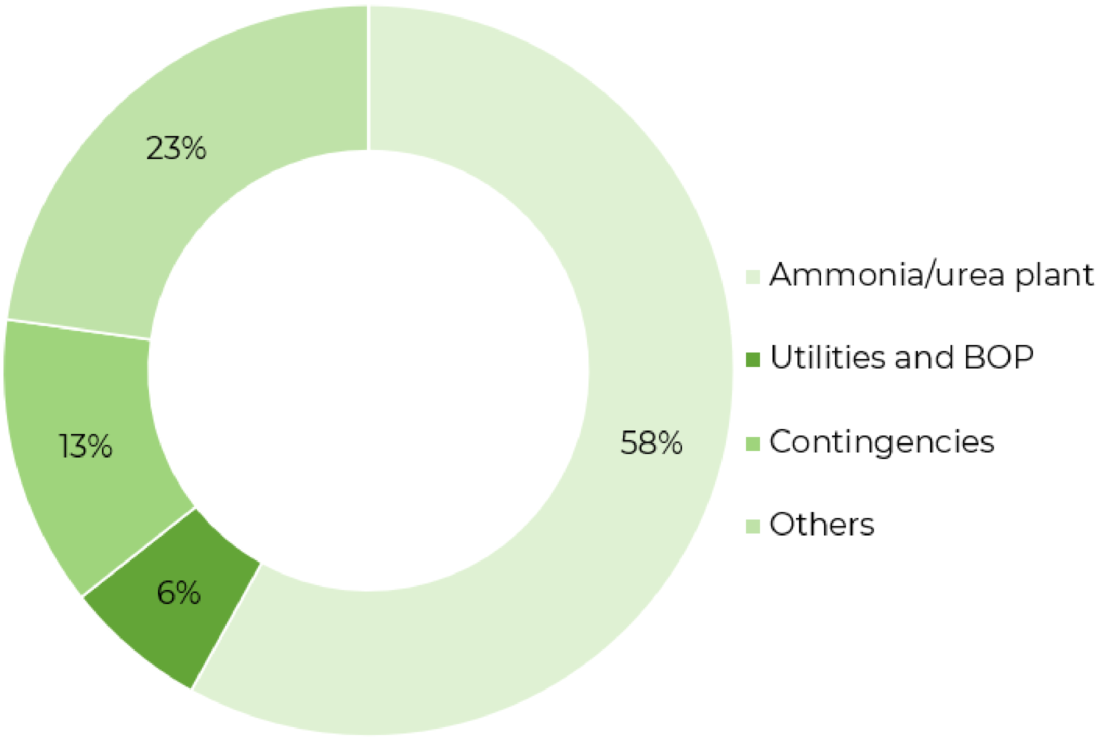


Figure 15: OpEx breakup for conventional urea production

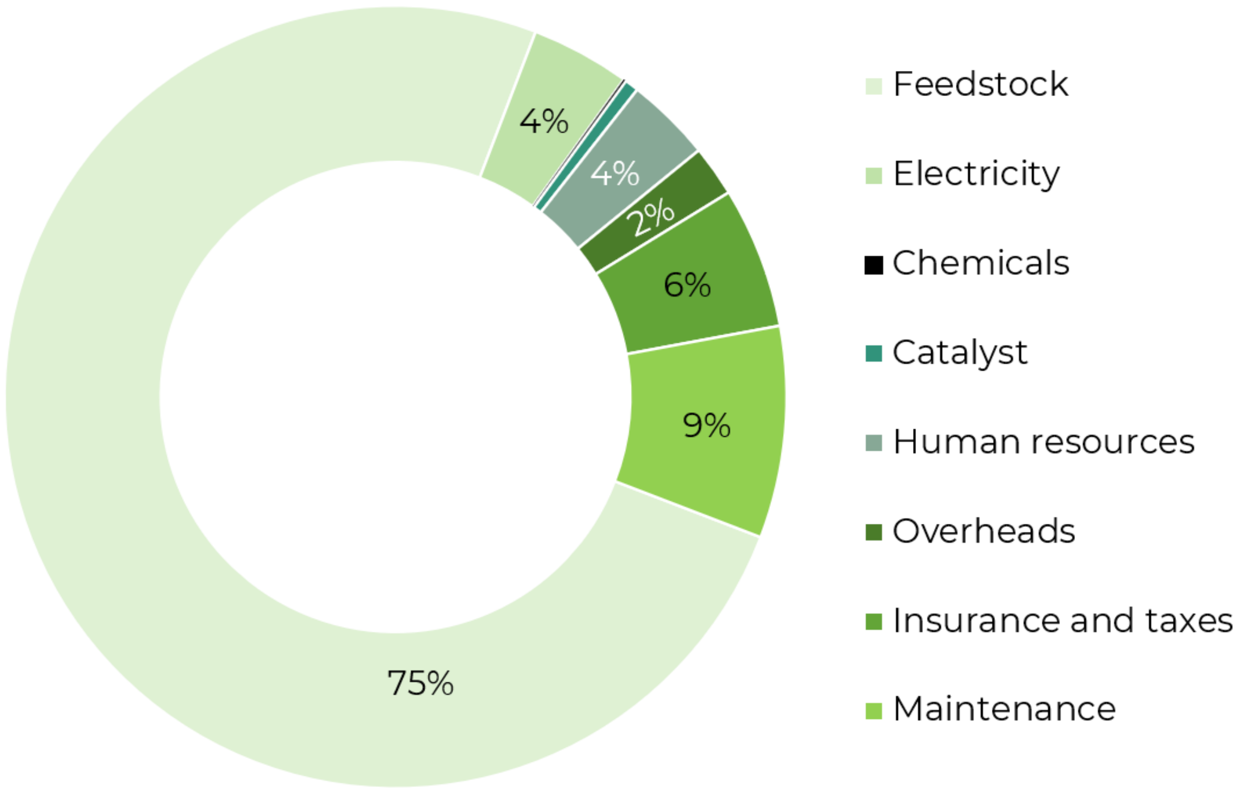
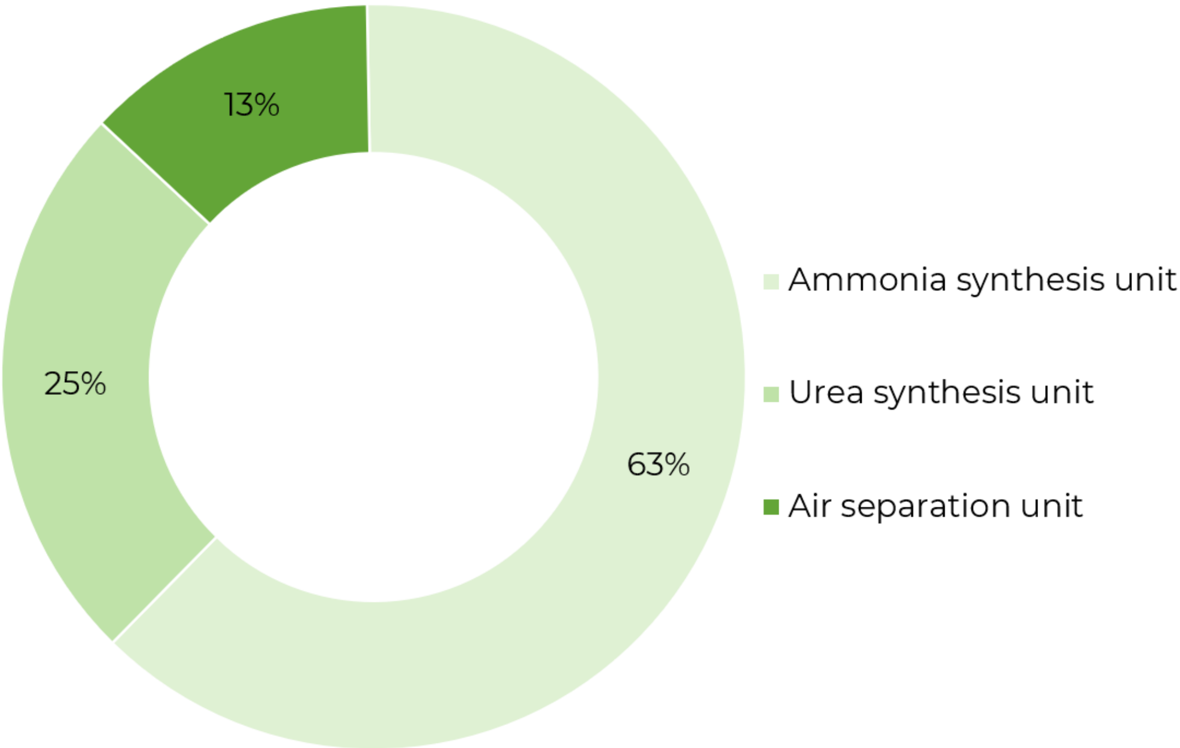


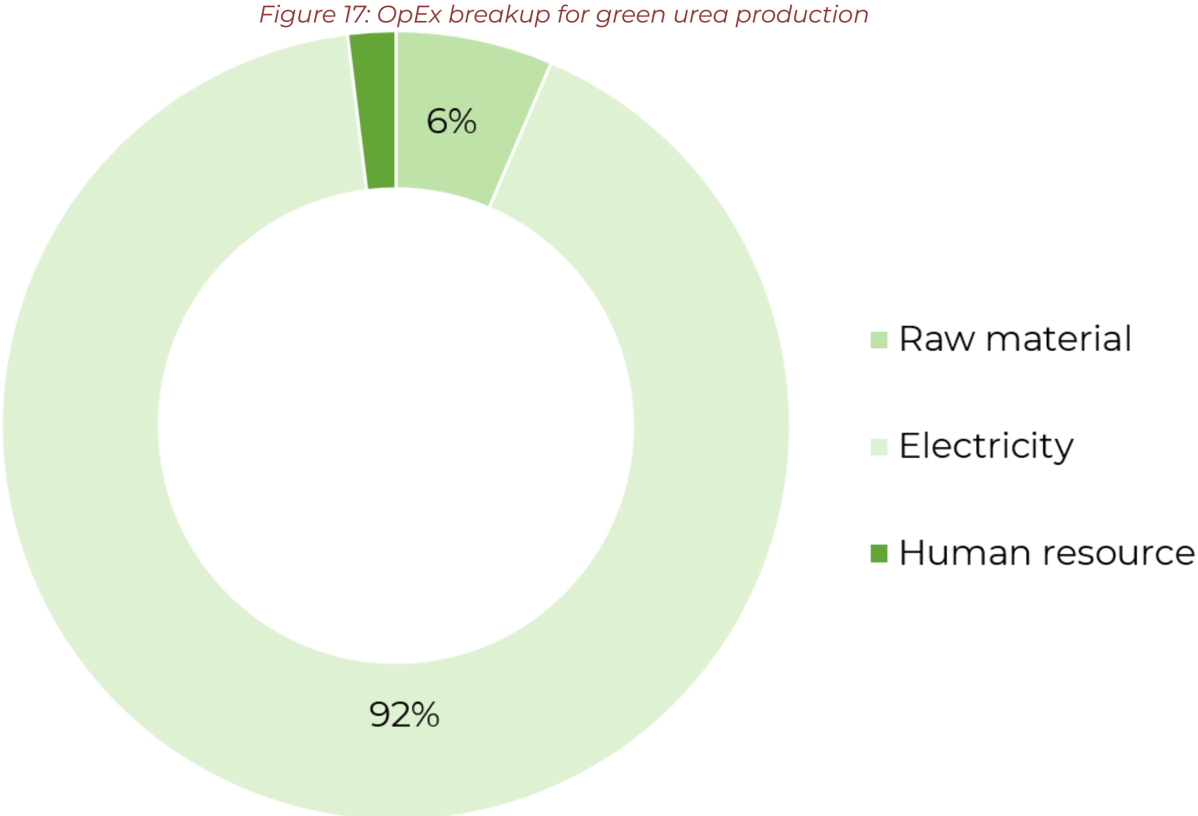
Figure 16 and Figure 17 show the breakup of CapEx and OpEx, respectively, for the green urea production process (Khan et al., 2024). It is observed that the NH_3 synthesis unit occupies the largest share (over 50%) in total CapEx.

Figure 16: CapEx breakup for green urea production



Within the OpEx, a significant portion is constituted by electricity expenses, primarily because the production of H_2 happens through electrolysis. Notably, Figure 17 indicates a lower share of raw material costs in the OpEx, unlike in conventional synthesis, as the only externally sourced raw materials are water and CO_2.

Figure 17: OpEx breakup for green urea production



4.3.2. Levelised Cost of Production

The levelised cost of production serves as a key metric for evaluating the lifetime cost of producing methanol or urea, considering their respective lifetime investments (including both CapEx and OpEx). The study considers the project life of both the plants to be 25 years. This metric provides a comprehensive assessment of the true cost of producing a product, expressed in INR per kg. It offers insights into the aspect of economic competitiveness and facilitates policy assessment and decision-making. In the present context, the cost of producing green methanol and green urea is compared with conventional costs. It is estimated using the formula given by Chen et al. (2021):

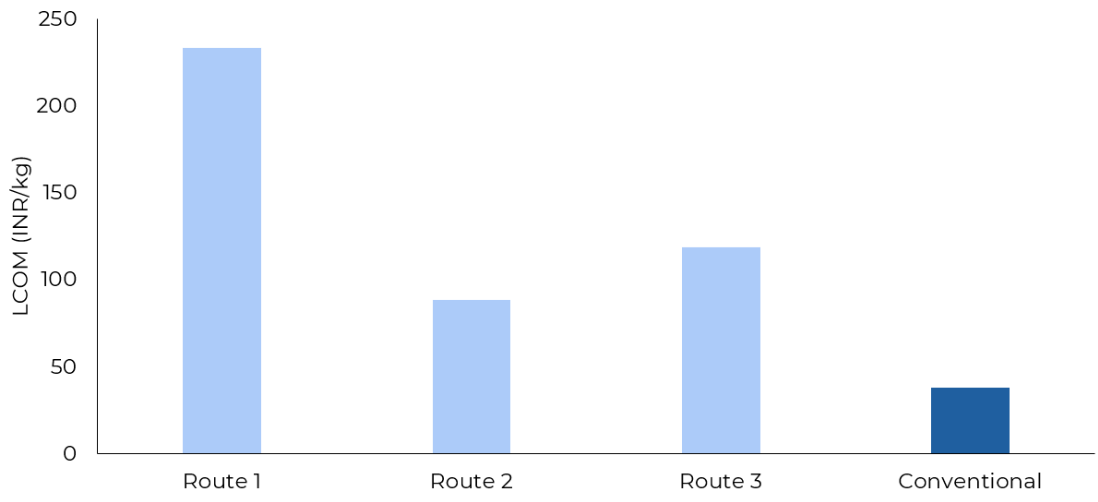
$$Levelised\ Cost\ = \frac{(CapEx + \sum_{1}^{t=25} OpEx)}{\sum_{1}^{t=25} Annual\ Production} \quad (1)$$

Levelised cost also guides in estimating the payback periods and net revenues for green methanol and urea plants.

4.3.2.1. Levelised Cost of Methanol

Figure 18 illustrates the levelised cost of methanol (LCOM) under CO_2-based approaches at a discount rate of 15% (Route 1, Route 2, and Route 3), and compares it with the conventional method. Route 1 offers an LCOM of INR 233 per kg while Route 2 and Route 3 produce methanol at an LCOM of INR 88 per kg and INR 119 per kg, respectively. As is evident, the CO_2-based approaches result in a higher LCOM compared to the traditional approach. However, a large-scale CO_2-based plant offers a slightly better low-cost option (as in Route 2 and Route 3). The LCOM of large-scale plants is twice that of the plants following the traditional approach. Hence, the **LCOM of Route 2 is considered for the impact analysis** presented in Section 6.

Figure 18: LCOM of various production processes

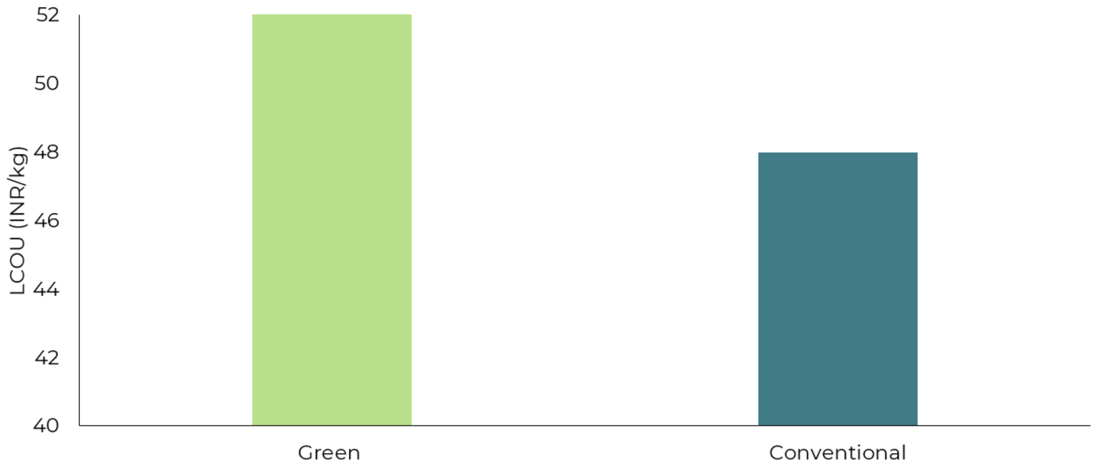


4.3.2.2. Levelised Cost of Urea

Similarly, the CO_2-based approach for urea production entails a higher levelised cost (INR 56 per kg or USD 0.68 per kg) calculated at a discount rate of 15%, as compared to that in the traditional approach (INR 6 per kg or USD 0.07 per kg).

Figure 19 presents the levelised cost of urea (LCOU) of green and conventional production routes. It can be inferred that the LCOU of the green process is 1.2 times that of the conventional process.

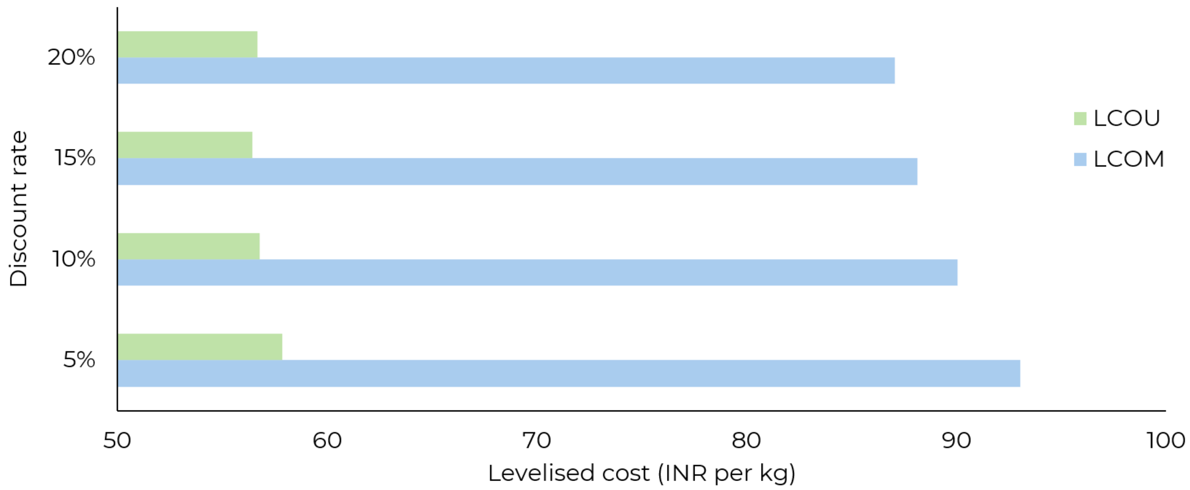
Figure 19: LCOU of various production processes



Impact of Variations in Discount Rates on Levelised Costs

The discount rate varies with interest rates on debt and equity, depending on the size of the project, linkages with government schemes, etc., Therefore, the levelised costs have been estimated for different discount rates to see the effect of variations, which are shown in Figure 20. As can be observed from the figure, the levelised cost of production decreases with an increase in the discount rate.

Figure 20: Effect on levelised cost with variation in discount rates



4.3.3. Results of Techno-Economic Assessment

This section discusses the techno-economic aspects of methanol and urea production using captured CO_2. The key components of techno-economic analysis include raw material requirement, electricity requirement, conversion efficiency, the associated costs (CapEx and OpEx), and levelised costs.

The results have been normalised for better comprehension in terms of CO_2 utilised per kg of methanol or urea produced, and H_2 utilised per kg of methanol or urea produced. This metric indicates the conversion efficiency of each raw material. Electricity requirement is expressed as kWh/kg of product. Further, the study also compares the plant configuration followed in different production approaches. This helps in identifying the difference in CapEx and OpEx costs, electricity usage, etc.

4.3.3.1. Results Summary: Green Methanol Production

For methanol production, the amount of CO_2 and H_2 utilised per kg and the electricity requirement per kg were assessed by performing material and energy mass balance analysis using DWSIM simulations.

Table 6 presents the summarised results of techno-economic analysis of methanol production. DWSIM forms the basis for Route 1 (two-step hydrogenation) and Route 2 (single-step hydrogenation), while Route 3 (Kim et al., 2011) is taken as an additional reference to validate the other production routes. Cost values are provided in normalised[2] form for better comprehension.

From the table, it can be inferred that DWSIM Route 1 has a significantly higher normalised CapEx and normalised annual OpEx than the other two routes. The levelised cost of production through this route is also much higher than the others. One of the reasons for this difference is lower plant capacity. The electricity requirement in Route 3 is significantly higher than the others, as it involves more electricity-based processing units than the other two routes.

Table 6: Results summary of green methanol production

Parameter	**Conventional approach** (as given in IEAGHG, 2017)	**DWSIM Route 1 (Two-step hydrogenation)**	**DWSIM Route 2 (Single-step hydrogenation)**	**Route 3 (Single-step hydrogenation)** (as mentioned by Kim et al., 2011)
Plant capacity (tph)	208	0.15	60	10
H_2 requirement (kg/kg product)	-	0.40	0.20	1.18
CO_2 requirement (kg/kg product)	-	2.45	1.48	1.84
Feed-to-methanol efficiency	-	64%	41%	-
Normalised CapEx (INR crore/tph)	46	405	17	18
Normalised OpEx (INR crore/year/tph)	22	110	60	82
Levelised cost (INR/kg)	38* (USD 0.46)	233 (USD 2.8)	88 (USD 1.05)	119 (USD 1.43)

*(*market cost)*

[2] Normalisation: CapEx in terms of INR crore per tonne of production in an hour; OpEx in terms of INR crore per year per tonne of production in an hour.

Given its low LCOM, high raw material conversion efficiency, and low feedstock requirement, methanol production via CO_2 hydrogenation (Route 2) was chosen as the green route of methanol production in this study.

4.3.3.2. Results Summary: Green Urea Production

Table 7 summarises the results of the techno-economic analysis of conventional and green urea production processes (Khan et al., 2024). Both processes employ the Stamicarbon approach for producing urea. As mentioned earlier, the source of raw materials is the main difference between the two production routes. The energy requirement is higher in the green urea case due to the production of H_2 via electrolyser (one kg of H_2 production requires 80 kWh of electricity). Further, the levelised cost of urea is also high in this case, as it requires green H_2 and captured CO_2 from point sources. The levelised cost of producing urea through green route is 1.2 times of that in the conventional route. However, the selling price of urea in the market (INR 5.4 per kg) is lesser due to the subsidy (the actual price of urea is INR 48 per kg).

Table 7: Results summary of green urea production

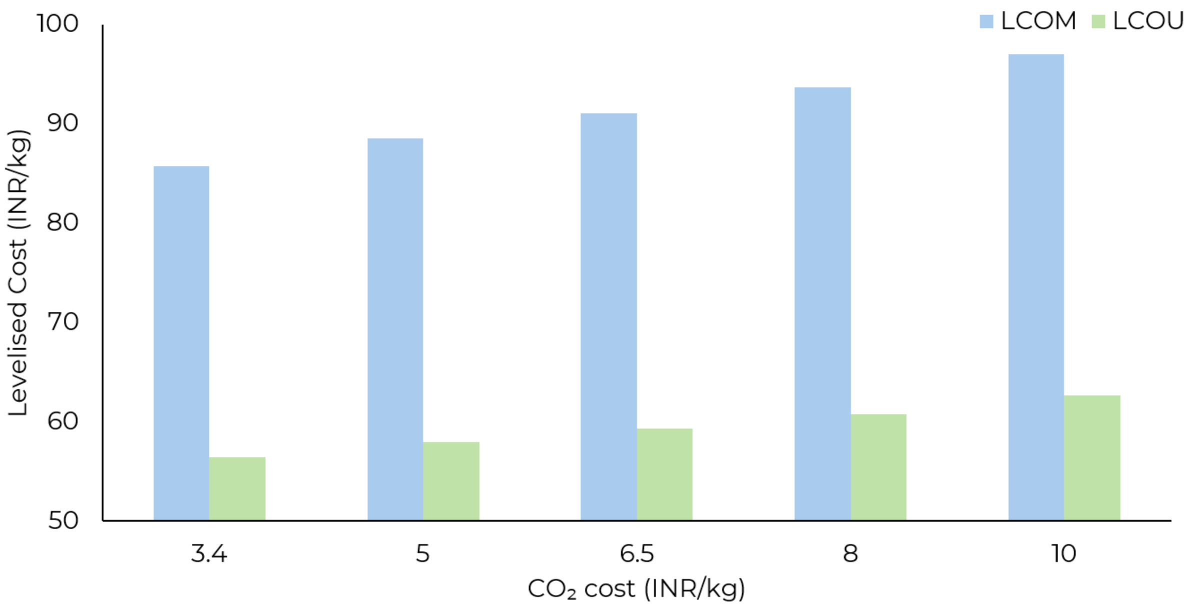
Parameter	**Conventional approach** (as outlined in IEAGHG, 2017)	**Green approach** (as outlined by Khan et al., 2024)
Plant capacity (tph)	94	58
H_2 requirement (kg/kg product)	0.1	0.1
CO_2 requirement (kg/kg product)	0.82	0.82
Feed-to-urea efficiency	-	72%
Normalised CapEx (INR crore /tph)	80	25
Normalised OpEx (INR crore /year/tph)	16	37
Levelised cost (INR/kg)	48 (USD 0.6)	56 (USD 0.67)

Impact of variations in buying cost of CO_2 on the levelised cost

At present, the costs of CO_2 are elevated primarily due to low supply, coupled with high demand in various critical applications such as food packaging, storage, fire extinguishers, etc. Large-scale carbon capture offers promise for substantially reducing CO_2 costs. As part of this exploration, a sensitivity analysis has been undertaken to evaluate the levelised costs with variations in the cost of CO_2.

Figure 21 presents the variation in levelised costs for different costs of CO_2. As can be seen, a reduction in CO_2 cost leads to a slight reduction in the levelised cost. This indicates that the cost of H_2 and other O&M expenses are strong factors that influence levelised cost.

Figure 21: Effect on levelised cost due to variations in CO_2 costs



4.4. Techno-Economic Assessment: Key Findings

Key Findings for Methanol

In the traditional methanol production route:

- the feed-to-product conversion efficiency is **63%;**
- for producing **1 kg of methanol**, **0.88 kg of CO** and **0.13 kg of H_2** are required.

In the hydrogenation route of methanol production (using CO_2 as feedstock):

- the feed-to-product conversion efficiency is **59–64%;**
- for producing **1 kg of methanol**, **1.48–2.45 kg of CO_2** and **0.2–0.4 kg of H_2** is required.

The traditional methanol production route:

- requires a **CapEx of INR 46 crore/tph** and an annualised **OpEx of INR 22 crore/tph;**
- current market cost of methanol is INR 38/kg

The hydrogenation route:

- requires a **CapEx of INR 16–18 crore/tph,** an annualised **OpEx of INR 60–82 crore/tph;**
- offers a levelised cost of INR 88–119/kg.

Key Findings for Urea

The urea production process (Stamicarbon):

- has a feed-to-product conversion efficiency of **77%;**
- requires **0.82 kg of CO_2** and **0.1 kg of H_2** as raw materials for producing **1 kg of urea**.

The traditional urea production route:

- requires a **CapEx of INR 80 crore/tph** and an annualised **OpEx of INR 16 crore/tph;**
- current market cost of urea is INR 48/kg (without subsidy).

The green urea production route:

- requires a **CapEx of INR 25 crore/tph** and an annualised **OpEx of INR 37 crore/tph;**
- offers a levelised cost of INR 56/kg.

5. Commercial Prospects

The commercial aspects of producing green methanol and green urea on an industrial scale can be understood by assessing the TRL of the considered technology. TRL, rated on a scale of 1 to 9, indicates the maturity of a technology. TRL 1 represents the lowest technology maturity (at basic research level) and TRL 9 indicates the highest technology maturity (commercial operations feasible).

In India, the conventional processes for producing methanol and urea are well established, and their TRLs are higher than that of their green counterparts. Table 8 shows the key producers of methanol and urea, along with the TRLs of their plants.

Table 8: Major Indian chemical producers and their TRLs

Chemical	Major Indian Producers	Production Process	Maximum Plant Capacity (MTPA)
Methanol	Gujarat Narmada Valley Fertilizers & Chemicals Limited (GNFC)	NG to methanol	1,59,840
Urea	Krishak Bharati Cooperative Limited (KRIBHCO)	NG to urea	18,27,200

Due to the growing awareness of climate change and stronger net-zero aspirations, green methanol and green urea plants have been receiving attention across the world. The George Olah Green Methanol plant in Iceland that operates on an industrial scale is a notable example. The plant's operations commenced in 2011, and its capacity was gradually increased from 1,300 to 4,000 tonnes per year. It utilises 5,500 tonnes of CO_2 emitted by a nearby power plant (Carbon Recycling International, 2022). However, there are no operational green urea plants currently, as the TRL for green urea production remains low.


CO_2

6. Impact Analysis

The impact analysis focussed on exploring the potential for reducing the imports of methanol and urea and fulfilling India's total domestic demand through the captured CO_2 route. It evaluates the long-term implications of green methanol and green urea production on the economy. Based on the current demand and imports of methanol and urea, the CO_2 raw material requirements for green methanol and green urea have been calculated. The analysis also includes a comparison of the total expenses on green methanol and green urea plants (over a period of 25 years) vis-à-vis the import bill for the same period.

Towards this, a scenario-based analysis has been performed considering different selling prices of methanol and urea, along with the CO_2 capture costs and manufacturing costs of green methanol and urea plants.

The impact analysis involves the following steps:

1. Assessing the imports of methanol and urea.
2. Assessing CO_2 emissions from key sectors (coal, cement, and iron and steel).
3. Identifying point sources of emissions.
4. Estimating the requirement of CO_2 (to be captured) to produce green methanol and green urea to avoid their imports and meet the domestic demand.
5. Estimating the investment costs of carbon capture and production of green methanol and green urea.
6. Performing scenario-based analysis with different selling prices to analyse revenues and payback periods.

6.1. Methodology

To examine the competitiveness of green methanol and green urea production against their imports, an assessment of their investment costs and the associated payback periods was made The investment cost of a plant with a given capacity has been calculated through the following formula, mentioned by Turton (2018):

$$CapEx\ of\ plant = Reference\ plant\ CapEx \times \left(\frac{Capacity\ of\ plant}{Reference\ plant\ capacity}\right)^{E} \quad (2)$$

where E is the scaling factor (generally taken as 0.67).

Further,

- The investment cost includes the cost of establishment of the methanol or urea plant and the carbon capture unit.
- The OpEx of the methanol and urea plant are taken as 3.65 times and 2.6 times of their investment costs, respectively.
- The OpEx of the carbon capture unit is taken as 20% of its investment cost.

Next, the revenue generated by the plant per day was calculated on the basis of the per day production of methanol or urea (as the case may be) and its selling price. In this study, the selling price is varied over a range of values (from levelised cost to market cost).

$$Revenue = Selling\ Price \times Daily\ Production \quad (3)$$

The gross revenue of production per year has been calculated through the equation given below, assuming that a plant operates on 333 days in a year.

$$Gross\ Revenue = Revenue \times Operating\ Days \quad (4)$$

However, since the operating costs of the methanol or urea production plant and the carbon capture unit are constant, the net revenue per year is given by:

$$Net\ Revenue = Gross\ Revenue - Annual\ OpEx \qquad (5)$$

Based on the net revenue, the payback period on investments can be calculated as:

$$Payback\ Period = \frac{Total\ CapEx}{Net\ Revenue} \qquad (6)$$

6.2. Raw Materials Required (to produce a quantity equivalent to imports)

Table 9 presents the current imports, domestic production, and total demand of methanol and urea for 2022. It indicates that India imported **94% of its methanol requirement and 26% of its urea requirement in FY 2021–22**.

Table 9: Demand, import, and production of methanol and urea in India (FY 2021-22)

Methanol	Methanol (MMT)	Urea (MMT)
Demand	2.55	34.17
Import	2.40	9.14
Production	0.17	25.07

The raw material requirements for producing methanol and urea are estimated considering the **methanol or urea mass ratio. Methanol production requires a feed with a CO_2:H_2 ratio of 0.14:1** and urea production require a feed with a **CO_2:NH_3** ratio of **1.3:1**. These values are stoichiometric but industrial processes require a feedstock that is 20–30% higher than the stoichiometric ratios. Accordingly, the quantity of different raw materials required for producing methanol and urea domestically (and to avoid the imports) has been estimated. Table 10 summarises this raw material requirement for methanol and urea to avoid the current imports.

Table 10: Raw material requirement

Purpose	Methanol (MMT)		Urea (MMT)		
	CO_2	H_2	CO_2	H_2	N_2
To avoid the imports	3.57	0.53	7.47	0.91	4.27
To meet the total demand	3.79	0.56	27.9	3.4	16

6.3. Potential Emissions from Key Sectors/Industries

The study assessed the potential CO_2-based emissions from coal-based power sector, key industries such as cement, iron and steel, and fertilisers, refineries, etc. Figure 22 presents the share of CO_2-based emissions from key sectors and industries in India (**totalling 2.6 Gt of CO_{2e}**). The emissions from these sectors are of two types: those from point sources and those from non-point sources. Point source emissions are released from a single source such as a coal power plant, steel plant, cement plant etc., while non-point source emissions come from multiple sources that include transport, residential, and other dispersed sources. Point sources (other than methane and fluorinated gases) provide the flexibility to capture a higher concentration and quantity of CO_2. Therefore, sector- or industry-specific capture technologies are usually designed to meet the requirements of point source emissions. As seen in Figure 22, **62% of the total emissions (1.6 Gt of CO_2)**

come from point sources (cement, power, iron and steel, and refineries), which carry the potential for easy CO_2 capture.

Figure 22: Sector- and industry-wise CO_2 emissions

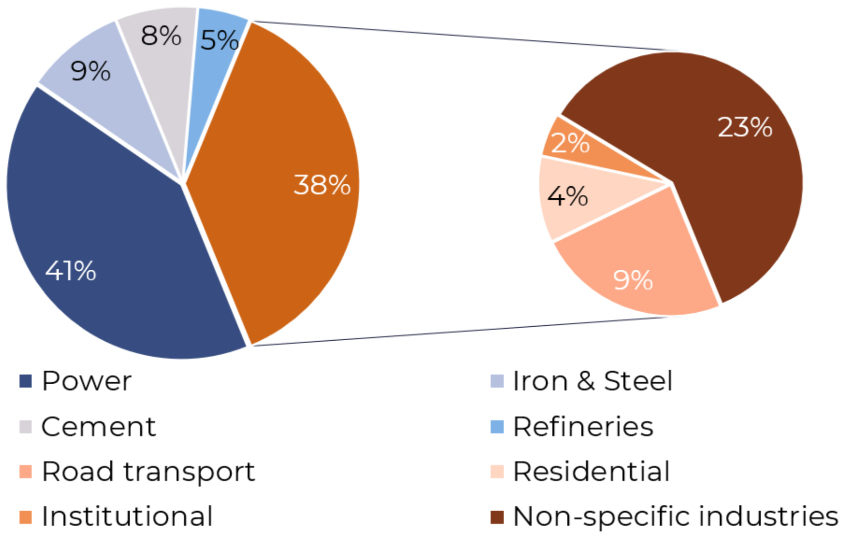
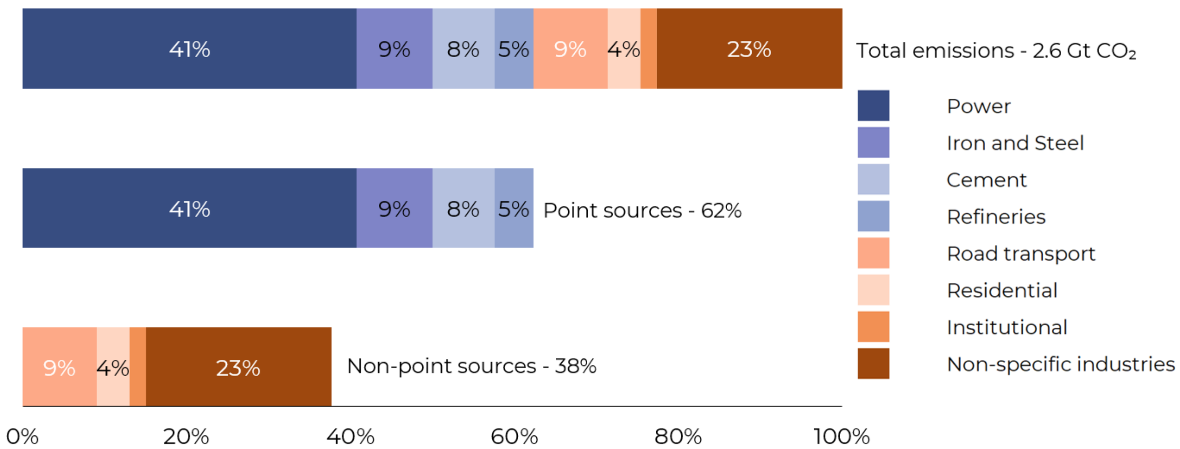


Figure 23 presents the breakup of emissions from different sectors and industries. **Point sources** and **non-point sources (including methane, hydrofluorocarbons, etc.)** contribute **62%** and **38%**, respectively, to the total emissions. Non-specific industries release different forms of emissions, such as nitrous oxide, fluorinated carbons, methane, etc. from agriculture, aluminium production, and manure management.

Figure 23: Point source and non-point source emissions



6.4. Potential CO_2 Requirement for Avoiding Imports and Meeting the Total Demand of Methanol and Urea

The potential CO_2 capture from point sources has been estimated on the basis of the total demand for chemicals (methanol and urea) and current imports. It is found that **0.22% of the CO_2 captured from point sources (1.6 Gt of CO_2)** is sufficient to avoid the **import demand of methanol.** Similarly for **urea**, **0.46% of the CO_2 captured from point sources** is required to avoid the import demand. **To meet the total demand, an additional 0.01%** and **1.26% of CO_2 is required** to be captured for **methanol** and **urea,** respectively. Figure 24 and Figure 25 show the quantity of chemicals required, along with the CO_2 to be captured for their production, to avoid imports and meet the total demand of methanol and urea.

Figure 24: CO_2 required to avoid imports and to meet the demand of methanol via green approach

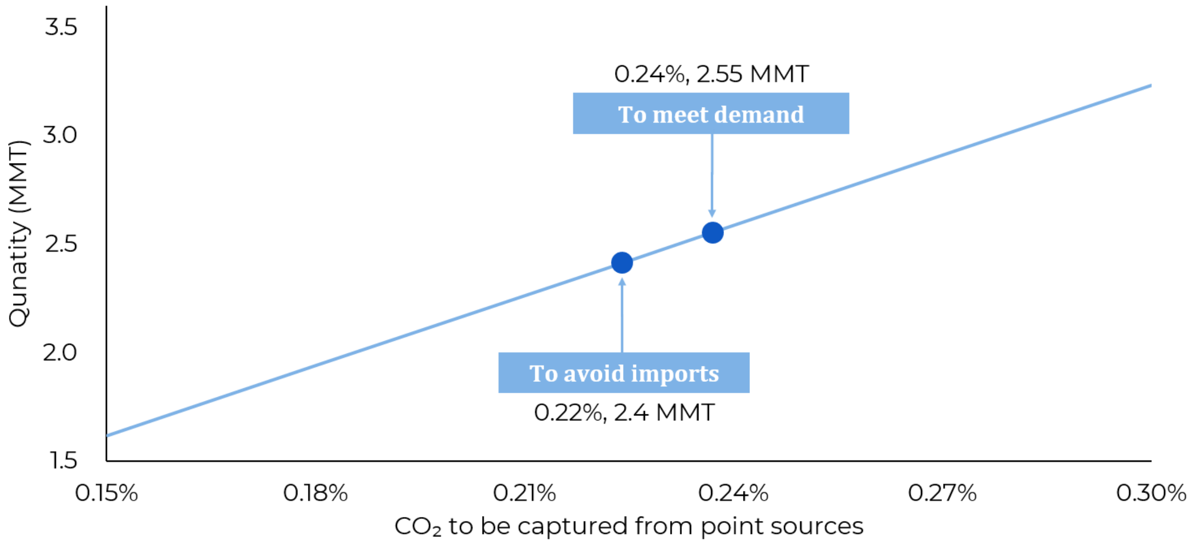
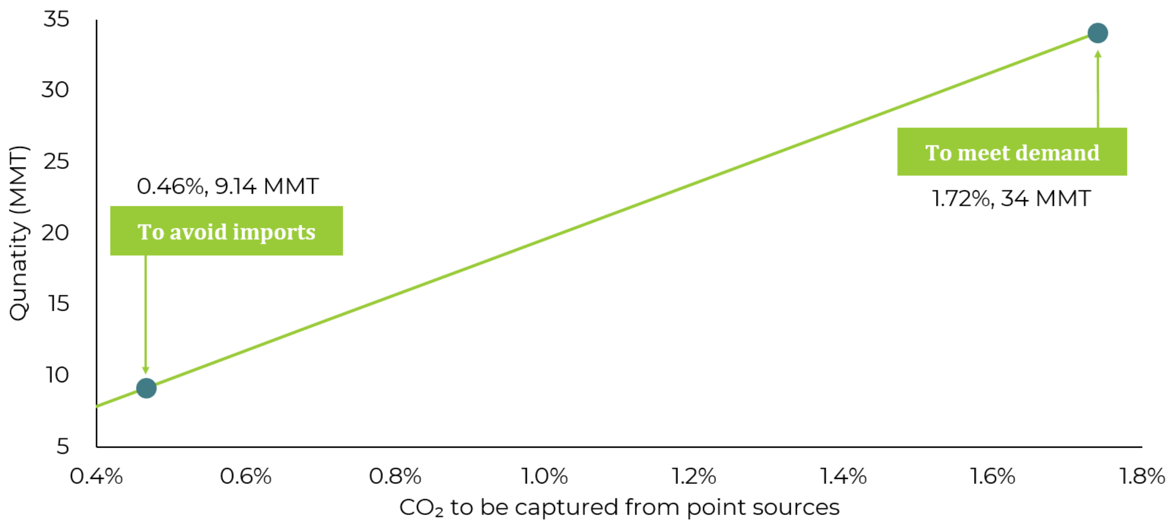


Figure 25: CO_2 required to avoid imports and to meet the demand of urea via green approach



6.5. Investment Needed to Avoid Imports and Meet Total Demand Through Green Route

This section details the investment that would be required to produce adequate amounts of green methanol and green urea to a) avoid imports; and b) meet the total domestic demand.

Table 11 provides the investment cost of capturing CO_2 in pilot plants from point-source-emissions sectors such as coal-based power and iron and steel, industries like cement, and refineries (NITI Aayog, 2022). A weighted average capture cost is calculated considering these reference costs. **The average cost of CO_2 capture is found to be INR 0.3 crore/MTPD.** However, the cost ranges from INR 0.3–1.0 crore/MTPD, depending on geographical location, plant capacity, and other factors.

Table 11: Investment cost for CO_2 capture

Sector	Plant capacity (MMTPA of CO_2)	Investment (INR crore)	Investment (INR crore per MTPD)
Power	5	3,750	0.25
Iron and Steel	2	1,800	0.30
Refineries	1	1,200	0.40
Cement	2	1,700	0.28

A comprehensive breakdown of the investment and operational costs of eliminating imports and meeting the entire domestic demand through captured CO_2 via the green route, is outlined below. Considering the vast amount of production required, it is assumed that the quantities are cumulatively produced by 15 methanol and 58 urea plants. The scaling factor has been taken as 0.7.

1. Green Methanol

a) Investment required for avoiding imports

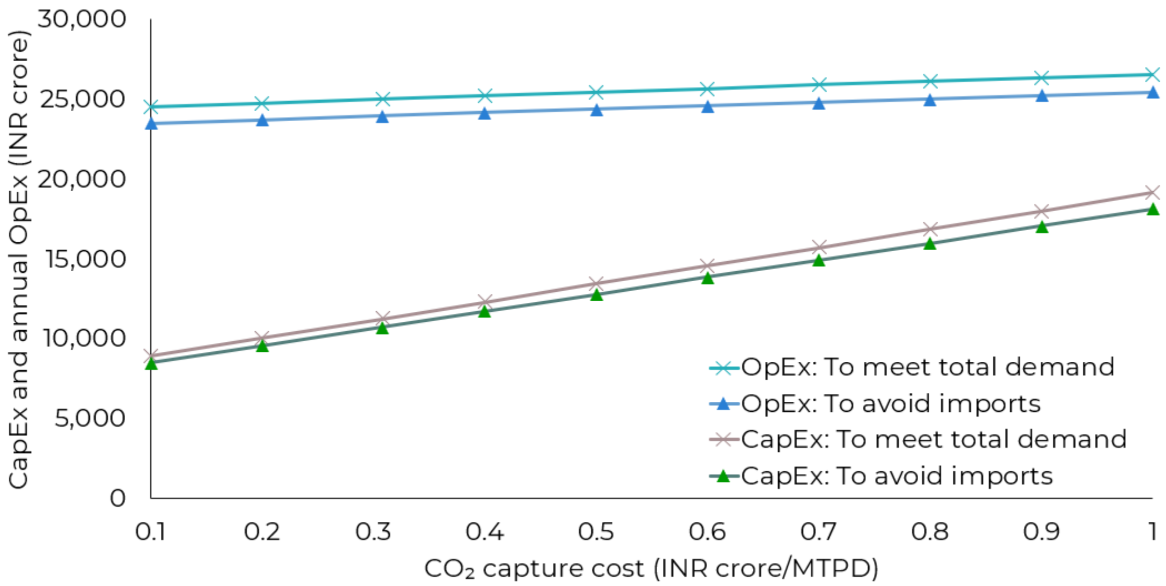
In terms of capture costs, the capital investment is calculated to be INR 3,300 crore, with an annual operational cost of INR 660 crore (OpEx is ~20% of CapEx). The capital investment required for CO_2 transportation is estimated to be INR 510 crore, with an annual operating cost of INR 2 crore. For methanol manufacturing, the capital investment amounts to INR 6,900 crore, accompanied by an operational cost of INR 23,290 crore per year. On considering both capture and manufacturing costs, a total capital investment of INR 10,700 crore and an annual operational cost of INR 23,960 crore (overall OpEx is ~224% of CapEx) is indicated.

b) Investment required for meeting total demand

In terms of capture costs, a capital investment of INR 3,500 crore would be needed, accompanied by an annual operational cost of INR 700 crore. The capital investment required for CO2 transportation is estimated to be INR 540 crore, with an annual operating cost of INR 2 crore. For methanol manufacturing, the capital investment amounts to INR 7,200 crore, with an annual operational cost of INR 24,300 crore. The combined capture and manufacturing costs indicate a total capital investment of INR 11,240 crore and an annual operational cost of INR 25,000 crore.

Figure 26 illustrates the investment (CapEx) and operating cost (OpEx) of methanol for the above two cases, for different costs of captured CO_2 (ranging from INR 0.1/MTPD to 1.0 crore/MTPD). It shows that the typical CapEx and OpEx required depend on the capture costs.

Figure 26: Investment and operating cost of green methanol (with different CO_2 capture costs)



2. Green Urea

c) Investment required for avoiding imports

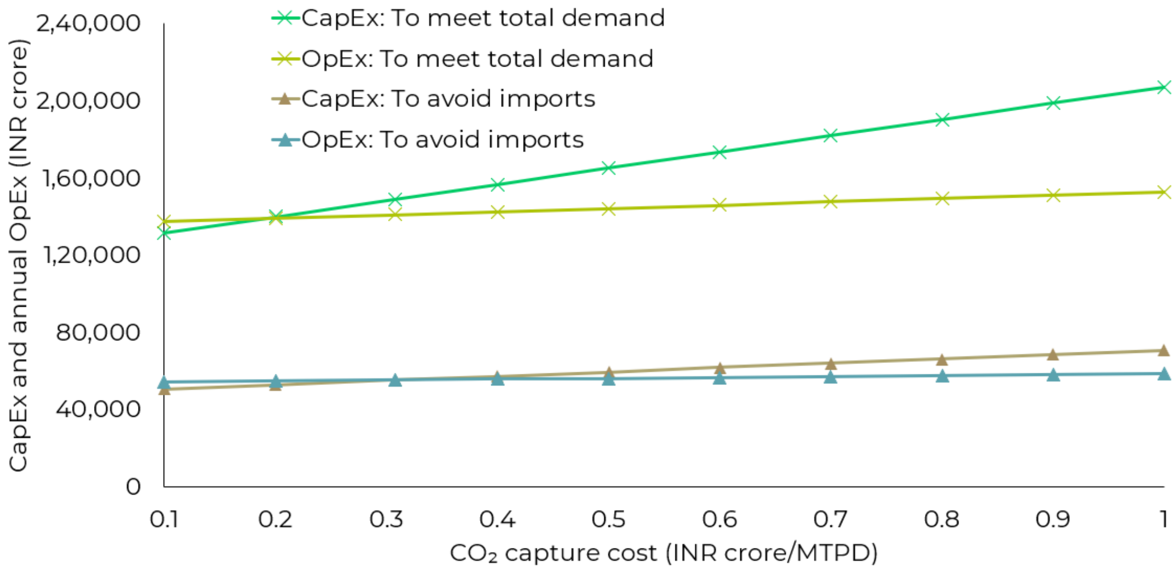
In terms of capture costs, the capital investment required is calculated to be INR 6,910 crore, accompanied by an annual operational cost of INR 1,380 crore. The capital investment required for CO_2 transportation is estimated to be INR 8,830 crore, with an annual operating cost of INR 35 crore. For urea manufacturing, the capital investment amounts to INR 39,460 crore, with an annual operational cost of INR 54,000 crore. On considering both capture and manufacturing costs, a total capital investment of INR 55,200 crore and an annual operational cost of INR 55,410 crore (overall OpEx is ~100.4% CapEx) is indicated.

d) Investment required for meeting total demand

In terms of capture costs, a capital investment of INR 25,840 crore would be needed, accompanied by an annual operational cost of INR 5,170 crore. The capital investment required for CO_2 transportation is estimated to be INR 23,850 crore, with an annual operating cost of INR 95 crore. For methanol manufacturing, the capital investment amounts to INR 99,350 crore, with an annual operational cost of INR 1,35,950 crore. The combined capture and manufacturing costs indicate a total capital investment of INR 1,49,040 crore and an annual operational cost of INR 1,41,220 crore.

Figure 27 presents the variation in CapEx and OpEx with different capture costs, for the above two cases.

Figure 27: Investment and operating cost of green urea (with different CO_2 capture costs)



Summary of investment requirement: Methanol	
Total capital investment (includes capture, transport, and manufacture) For avoiding imports: **INR 10,700 crore** For meeting total demand: **INR 11,240 crore**	**Total operating cost** (includes capture, transport, and manufacture) For avoiding imports: **INR 23,960 crore/year** For meeting total demand: **INR 25,000 crore/year**

Summary of investment requirement: Urea	
Total capital investment (includes capture, transport, and manufacture) For avoiding imports: **INR 55,200 crore** For meeting total demand: **INR 1,49,040 crore**	**Total operating cost** (includes capture, transport, and manufacture) For avoiding imports: **INR 55,400 crore/year** For meeting total demand: **INR 1,41,220 crore/year**

6.6. Revenue and Payback Periods

Factoring in the cost of CO_2 (as INR 3.4 per kg), the **LCOM** is estimated to be **INR 88 per kg.** This cost can come down to **INR 82 per kg, if CO_2 is supplied free of cost**. Similarly, the **LCOU** is estimated to be **INR 56 per kg**, considering the same cost of CO_2 (mentioned above). This cost can come down to **INR 53 per kg if CO_2 is provided free of cost.** In India, the actual price of urea is INR 48 per kg (and its subsidised rate is INR 5.4 per kg).

As mentioned earlier, the potential revenues and payback periods of the methanol and urea plants are assessed by varying their selling prices. Figure 28 and Figure 28Figure 29 illustrate the net revenue and payback period for methanol and urea plants, respectively.

Figure 28: Net revenue and payback period based on the selling price of methanol

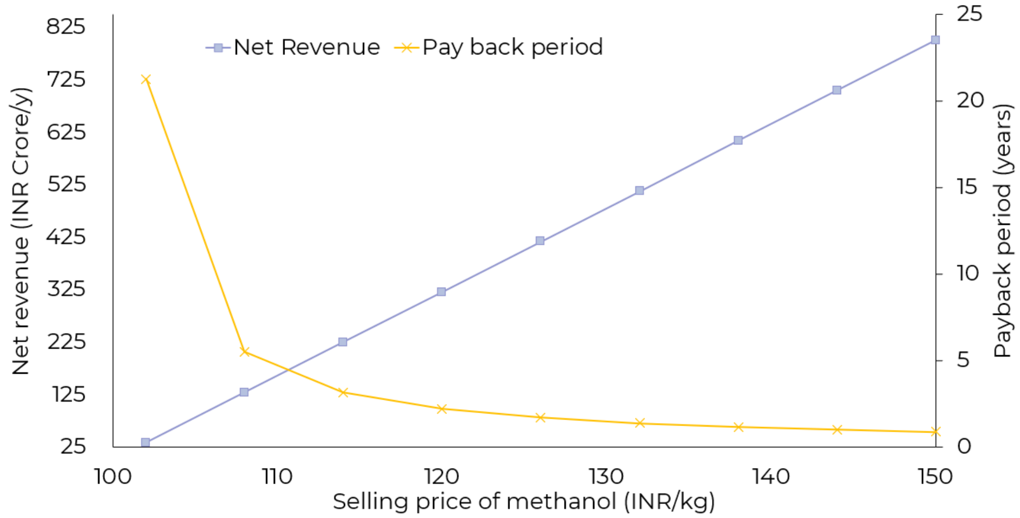
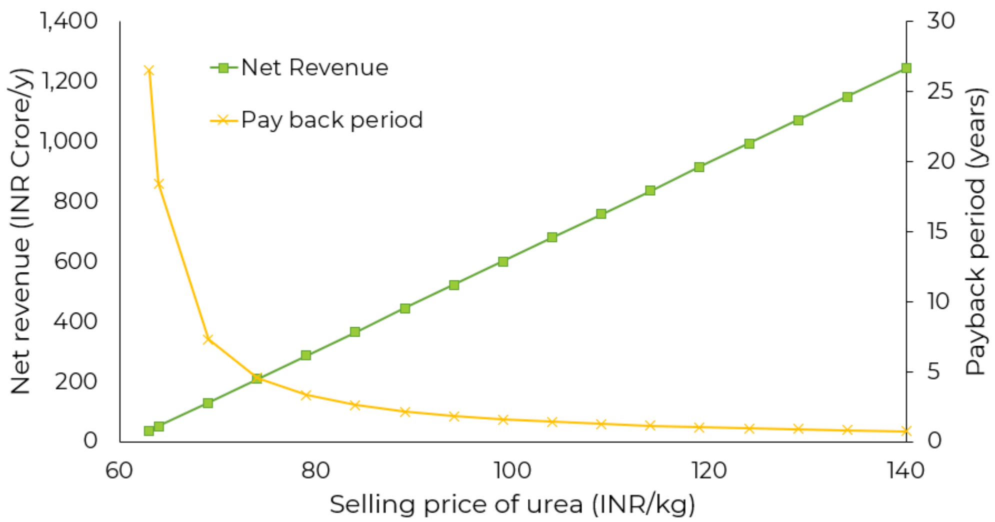


Figure 29: Net revenue and payback period based on the selling price of urea



The estimation of net revenue and payback period considers a CO_2 capture investment cost of **INR 0.31 crore/MTPD**. It can be observed that selling methanol at a cost of **INR 103 per kg** (USD 1.23 per kg) generates a net revenue of **INR 49.55 crore/year** and offers a 14.4-year payback period. If the capture investment is **INR 1 crore/MTPD**, the plant would require 19.7 years to achieve the break-even investment and generate a net revenue of **INR 62.54 crore/year** at a selling price of INR 110 per kg.

For urea, a threshold selling price of **INR 65 per kg** (USD 0.78 per kg) is required to realise positive cash-flows, if the capture investment cost is **INR 0.31 crore/MTPD**. Selling urea at this cost generates a net revenue of **INR 69.72 crore/year** and the break-even is achieved in 14 years. The threshold selling price increases to **INR 75 per kg** (or USD 0.9 per kg) if the capture investment cost is **INR 1 crore/MTPD**. Such a plant generates a net revenue of **INR 173.53 crore/year** and offers a payback period of 7 years.

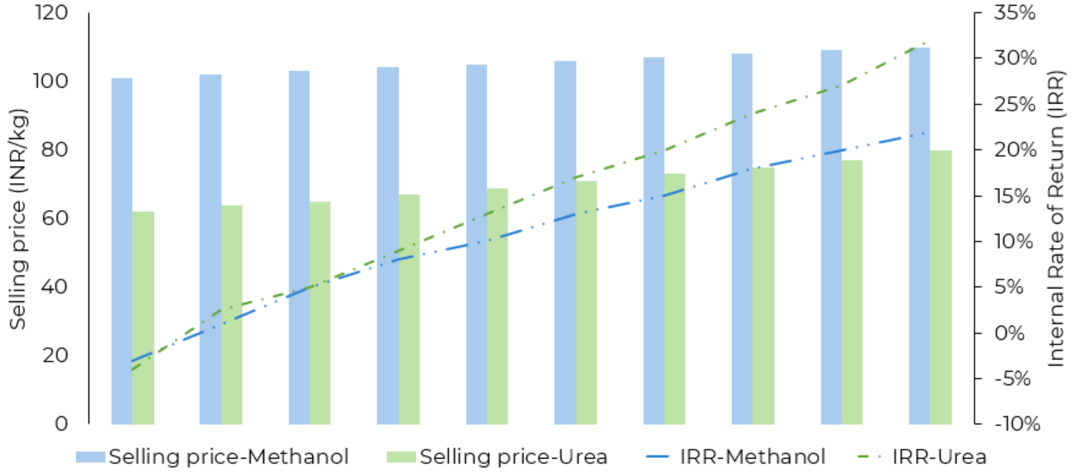
6.7. Internal Rate of Return

The internal rate of return (IRR) measures the profitability of a potential investment. The following formula is used to determine IRR:

$$Net\ Present\ Value = \sum_{0}^{n=25} \frac{Net\ cashflows}{(1+IRR)^n} \quad (7)$$

Figure 30 shows how the IRR changes with the selling prices of methanol and urea.

Figure 30: IRR variation with the selling price of product



If methanol is sold at **INR 101 per kg,** the **IRR** is **-3%**. However, a slight increase in the selling price of methanol to **INR 103 per kg** results in an IRR of **5%**. Similarly, if urea is sold at **INR 62 per kg,** the **IRR** is **-4%**. However, if it is sold at **INR 65 per kg,** the **IRR** increases to **5%**. The increase in IRR is due to the assumption of producing an amount of urea and methanol that is equivalent to their imports.

6.8. Potential Impact on the Economy

The impact of shifting from imported chemicals/chemicals produced domestically using fossil fuels to those produced domestically employing the green approach can be studied particularly in terms of the import bill of methanol and urea, the profitability of green methanol and green urea plants, and the resource availability (CO_2 capture) for producing them.

- **Import bill:**
  - India spends INR 7,380 crore per year on methanol and INR 47,170 crore per year on urea (a total of INR 54,550 crore per year) for imports.
  - An investment of INR 10,700 crore and INR 55,200 crore on methanol and urea, respectively, would avoid imports, eliminating import expenses of INR 1,84,570 crore (for methanol) and INR 11,79,250 crore (for urea) over a period of 25 years.

- **Profitability aspects:**
    - Optimistic Economic Outlook for Green Methanol Production:
        - Selling methanol at INR 103 per kg results in a net revenue of INR 743 crore per year (INR 50 crore per year per plant) and has a payback period of 14.4 years with a plant capacity 20 tph.
    - Optimistic Economic Outlook for Green Urea Production:
        - Selling urea at INR 65 per kg results in a net revenue of INR 3,974 crore per year (INR 70 crore per year per plant) and has a payback period of 14 years with a plant capacity 20 tph.
    - A substantial savings of INR 1,92,439 crore for methanol and INR 12,25,155 crore for urea can be realised by prioritising CO_2-based technologies for producing these chemicals, instead of relying on imports. These values have been estimated under the assumption of the current import demand. However, the demand of these chemicals is expected to grow, which could potentially lead to higher savings.
- **Resources requirement:**
    - **0.22%** of the captured CO_2 (3.57 MMT) obtained from the power and the iron and steel sectors, the cement industry, and refineries can meet the **import demand of methanol.**
    - **0.46%** of the captured CO_2 (7.47 MMT) obtained from the power and the iron and steel sectors, the cement industry, and refineries can meet the **import demand of urea.**
    - The amount of hydrogen required to produce green methanol and urea for meeting the domestic demand is 1.44 MMT (28.8% of the 2030 national hydrogen target).

7. Conclusion

India's demand for methanol and urea is steadily increasing. In FY 2021–22, the country's consumption of methanol and urea reached 2.5 MMT and 34.17 MMT, respectively. Notably, the country imported significant quantities—2.40 MMT of methanol and 9.14 MMT of urea—during this period, spending INR 7,380 crore on methanol imports and INR 47,170 crore on urea imports. During the same period, the country emitted 2.6 Gt of CO_{2e}, with key contributions from the coal-based power and iron and steel sectors, cement industry, and refineries. Of this, 1.6 Gt of CO_2 emission came from point sources alone (62%).

This study explored the techno-economic feasibility of producing methanol and urea using captured CO_2 from point source emissions. It found that to meet India's import demand of methanol (2.4 MMT) and urea (9.2 MMT), only 0.22% and 0.46% of CO_2 needs to be captured from the point sources.

According to the study estimates, green methanol production has a levelised cost of INR 88.13 per kg (USD 1.06 per kg), while green urea has a levelised cost of INR 56.44 per kg (USD 0.68 per kg). It was found that investing INR 10,700 crore in methanol and INR 55,200 crore in urea production could eliminate India's reliance on imports. Additionally, over a 25-year period (lifespan of a methanol or urea plant), there exists a potential to realise monetary savings of INR 1.92 lakh crore and INR 12.23 lakh crore, respectively, from green methanol and green urea production. Moreover, crude oil imports can be reduced by 44 MMT (viz., 15% of current imports), translating into a monetary benefit of INR 3,282 crore (considering the price of crude oil as USD 81.97 per barrel [as of 13 June 2024]), if the proposed 15% methanol blending with petrol succeeds. Further, natural gas usage could reduce by at least 5 MMT annually (resulting in savings of INR 19,500 crore) if green methanol and green urea are produced, instead of being imported. Although the initial investment for setting up green methanol and urea production units is significant, a break-even is achievable in 14 years, if the products are priced at INR 103 per kg (USD 1.23 per kg) and INR 65 per kg (USD 0.78 per kg), respectively. Finally, producing an amount of green methanol and green urea that is equivalent to their imported quantities, could abate 3.57 MMT and 7.47 MMT of CO_2, respectively. The analysis also finds that the carbon abatement cost would be INR 47–48 per kg (USD 0.56–0.58 per kg).

Our study shows that the methods for producing green methanol and green urea involve capturing CO_2 from fossil-fuel-based industries and obtaining H_2 from electrolysis. Technologically, these methods face minimal challenges. However, due to the higher production costs, they currently face barriers in terms of market competitiveness. As the study indicates, offering abatement cost as incentives can ensure quicker payback periods. Additionally, the government should devise strategies to promote CO_2 capture from fossil-fuel-based industries, incentivise it by providing capital and subsidising raw materials, and facilitate competitive pricing for these fuels to ensure their commercial viability and sustenance, as well as to support the goals of *Atmanirbhar Bharat*.


H2N
OH
MeO
MeO
OMe
N
Cl
OH
HO
HO
HO

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9. Appendix

Table A 1 presents the stoichiometric requirement of raw materials for production of green methanol and urea.

Table A 1: Stoichiometric requirement of raw materials for green methanol and urea production

Raw Material	Methanol	Urea
CO_2 (kg/kg product)	1.38	0.82
H_2 (kg/kg product)	0.19	0.1
N_2 (kg/kg product)	-	0.47

Table A 2 lists the various process equipment used in different methods of methanol production. Route 1 represents a two-step hydrogenation process and Route 2 represents a single-step hydrogenation process. As can be seen, Route 2 requires a greater number of heaters/coolers and compressors due to the higher plant capacity.

Table A 2: Equipment comparison between Route 1 and Route 2 (for methanol production)

Equipment	DWSIM Route 1 (Two-step hydrogenation)	DWSIM Route 2 (Single-step hydrogenation)
Reactors	2	1
Heat Exchangers	-	1
Heaters/Coolers	-	8
Vapour-Liquid Separators	2	2
Compressors	2	7
Absorber Units	-	1
Distillation Columns	1	1
Pumps	-	1
Valve Inlet	-	2

Table A 3 lists the various process equipment used in different methods of urea production. As can be seen, the green urea process uses lesser equipment than the traditional process since it does not involve treatment of NG. Instead, an ASU is present, from which N_2 is obtained.

Table A 3: Equipment comparison between Route 1 and Route 2 (for urea production)

Equipment/Unit	Traditional Urea	Green Urea
Gasification	1	-
Water Gas Shift	1	-
CO_2 Capture	-	1
Other Olefins Cracking	1	-
Methanation	1	-
Air Separation	-	1
Ammonia Synthesis	1	1
Urea Synthesis	1	1

Table A 4 shows the variation in LCOM and LCOU with changes in discount rate. The general trend observed is that LCOM and LCOU reduce with an increase in the discount rate.

Table A 4: LCOM and LCOU calculated for different discount rates

Discount rate	LCOM (INR per kg)	LCOU (INR per kg)
5%	93.04	57.86
10%	90.05	56.77
15%	88.13	56.44
20%	87.08	56.68

Tables A 5–A 8 display the variation in LCOM with changes in discount rate and raw material prices. It can be observed that the LCOM increases with an increase in raw material prices but reduces with increase in discount rate.

Table A 5: Impact of varied discount rates and H_2 costs on LCOM at a CO_2 cost of INR 3.4 per kg

Particulars	Discount rate			
Hydrogen cost (INR per kg)	5%	10%	15%	20%
250	80	78	76	76
290	91	88	86	85
330	101	97	95	94
370	111	107	105	103
410	121	117	114	112

Table A 6: Impact of varied discount rates and H_2 costs on LCOM at a CO_2 cost of INR 5 per kg

Particulars	Discount rate			
Hydrogen cost (INR per kg)	5%	10%	15%	20%
250	83	81	79	78
290	93	90	891	87
330	104	100	98	97
370	114	110	107	106
410	124	120	117	115

Table A 7: Impact of varied discount rates and H_2 costs on LCOM at a CO_2 cost of INR 6.5 per kg

Particulars	Discount rate			
Hydrogen cost (INR per kg)	5%	10%	15%	20%
250	86	83	82	81
290	96	93	91	90
330	106	103	101	99
370	117	113	110	108
410	127	122	119	118

Table A 8: Impact of varied discount rates and H_2 costs on LCOM at a CO_2 cost of INR 8 per kg

Particulars	Discount rate			
Hydrogen cost (INR per kg)	5%	10%	15%	20%
250	89	86	84	83
290	99	96	94	92
330	109	105	103	102
370	119	115	112	111
410	129	125	122	120

Table A 9: Impact of varied discount rates and H_2 costs on LCOM at a CO_2 cost of INR 10 per kg

Particulars	Discount rate			
Hydrogen cost (INR per kg)	5%	10%	15%	20%
250	93	90	88	87
290	103	99	97	96
330	113	109	106	105
370	123	119	116	114
410	133	129	125	123

Table A 10 shows the IRR calculated for various selling prices of methanol. It is observed that increasing the selling price provides a higher IRR.

Table A 10: IRR calculated for different selling prices of methanol

Selling price (INR per kg)	**IRR**
101	-3%
102	1%
103	5%
104	8%
105	10%
106	13%
107	15%
108	18%
109	20%
110	22%

Table A 11 shows the IRR calculated for various selling prices of urea. It is observed that increasing the selling price provides a higher IRR.

Table A 11: IRR calculated for different selling prices of urea

Selling price (INR per kg)	**IRR**
62	-4%
64	2.5%
65	5%
67	9%
69	13%
71	17%
73	20%
75	24%
77	27%
80	32%

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