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Decarbonization of urea production in India and its impact on water withdrawal and costs: A cost optimization approach

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ABSTRACT

Urea, a globally dominant synthetic nitrogen fertilizer, presents a complex challenge for India. While promoting agricultural productivity, its production—reliant on natural gas—is projected to drive a threefold increase in India's natural gas consumption by 2050. To meet ambitious climate targets while ensuring food security, India's existing urea plants must be decarbonized. This study conducted techno-economic modeling of "blue" and "green" urea production techniques for all 34 existing urea plants in India, incorporating technologies such as electrolyzers and carbon capture. Using a mixed-integer programming approach from a central planner's perspective, we evaluated key indicators of business-as-usual and decarbonization pathways for the sector under different scenarios. The results indicate that a high level of decarbonization is economically feasible under most scenarios, with the base scenario showing a potential adoption of over 93% green urea by 2050, thus reducing the sector's current natural gas consumption intensity of 645 $\frac{SCM}{t_{urea}}$ by 96%. This transition also results in a lower freshwater withdrawal intensity of approximately 4 $\frac{m^3}{t_{urea}}$, which is below India's current average of 6.4 $\frac{m^3}{t_{urea}}$. The levelized costs of urea for the decarbonization pathway are more robust against external factors, ranging from 398 to 487 $\frac{USD_{2026}}{t_{urea}}$, depending on the scenario. However, these costs must compete with the internationally traded urea prices, which fluctuated between 202 and 925 $\frac{USD}{t_{urea}}$ from 2019 to 2024, largely driven by natural gas prices. Low future natural gas prices could be a key barrier to achieving decarbonization and reducing the water intensity of urea. This study suggests that implementing a carbon tax could serve as an effective mitigation strategy in such cases. Future research should consider the integrated modeling of hydrogen and ammonia demands, which are relevant green fuels for the energy transition.

Nomenclature

Symbol	Unit	Description
Variables		
$B^{Gray}(t,cp)$ or $B^{Blue}(t,cp)$ or $B^{Green}(t,cp)$	–	Boolean value (1 or 0) indicating the operating/decommissioned condition of a current plant. Gray/blue/green indicate its possible activities
$C_{CO2Capture}$	$\frac{USD}{a}$	Total annual cost on capturing CO_2 (internal as well as external CO_2 source) aggregated across all the operating urea plants in India
$C_{CO2Emission}$	$\frac{USD}{a}$	Total annual cost on CO_2 tax aggregated across all the operating urea plants in India
C_{Import} or $C_{ImportElec}$ or $C_{ImportNG}$ or $C_{ImportWater}$	$\frac{USD}{a}$	Total annual cost for the purchase or import of urea, green electricity, natural gas and freshwater respectively aggregated across all the operating urea plants in India
$C_{Invest,FP}$	$\frac{USD}{a}$	Annualized investment cost for all the operating future plants (gray and green)
$C_{OMVar,CP}$	$\frac{USD}{a}$	Annual variable operating cost for all the operating current plants *CP*

(*continued on next page*)

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(*continued*)

Symbol	Unit	Description
$\boldsymbol{C_{OMFix,FP}}$	$\frac{USD}{a}$	Annual fixed operating cost for all the operating future plants (gray and green)
$\boldsymbol{N^{O^*}_{FP\_Gray}}(t)$ or $\boldsymbol{N^{O^*}_{FP\_Green}}(t)$	–	Total integer number of operating gray (or green) future plants at a given hour t
$\boldsymbol{N^{T^*}_{FP\_Gray}}$ or $\boldsymbol{N^{T^*}_{FP\_Green}}$	–	Total integer number of installed gray (or green) future plants
$\boldsymbol{Q^{Gray}_{CO2Emission}}(t,cp)$ or $\boldsymbol{Q^{Blue}_{CO2Emission}}(t,cp)$	$\frac{t_{CO_2}}{h}$	CO_2 emitted to the atmosphere by a current plant using a gray/blue technique at a given hour
$\boldsymbol{Q_{CO2Emission,FP\_Gray}}(t)$	$\frac{t_{CO_2}}{h}$	CO_2 emitted to the atmosphere by all the gray future plants at a given hour
$\boldsymbol{Q^{Gray}_{ureaProd}}(t,cp)$ or $\boldsymbol{Q^{Blue}_{ureaProd}}(t,cp)$ or $\boldsymbol{Q^{Green}_{ureaProd}}(t,cp)$	$\frac{t_{urea}}{h}$	Urea produced by a current plant using a gray/blue/green technique at a given hour
$\boldsymbol{Q_{ureaProd,FP\_Gray}}(t)$ or $\boldsymbol{Q_{ureaProd,FP\_Green}}(t)$	$\frac{t_{urea}}{h}$	Urea produced by all the gray (or green) future plants at a given hour
$\boldsymbol{Q_{ureaImport}}(t)$ or $\boldsymbol{Q_{ureaExport}}(t)$	$\frac{t_{urea}}{h}$	India's total urea import/export at a given hour
$\boldsymbol{R_{export}}$	$\frac{USD}{a}$	Total annual revenue through the export of urea aggregated across all the operating urea plants in India
Parameters		
$Cap(cp)$	$\frac{t_{urea}}{h}$	Installed capacity of a current plant
Cap_{fp}	$\frac{t_{urea}}{h}$	Installable capacity of the reference future plant
$c^{Gray}_{OMVar}(cp)$ or $c^{Blue}_{OMVar}(cp)$ or $c^{Green}_{OMVar}(cp)$	$\frac{USD}{t_{urea}}$	Specific variable operating cost of a current plant using the gray/blue/green urea technique
$f_{annuity}$	–	Annuity factor
i	–	Discount rate
P_{refCap}	$\frac{Mt_{urea}}{a}$	Production capacity of the reference future urea plant
$Q^{Blue}_{CO2Dem}(cp)$ or $Q^{Green}_{CO2Dem}(cp)$	$\frac{t_{CO_2}}{h}$	Make-up amount of process CO_2 captured, either internally (blue technique) or from an external source (green technique) for the urea synthesis process in a given current plant
Q_{CO2Dem,fp_Green}	$\frac{t_{CO_2}}{h}$	Amount of process CO_2 captured at an external source for urea synthesis process in reference green future plant
$Q^{Green}_{ElecDem}(cp)$	$\frac{kWh}{h}$	Green electricity consumed by the core technologies of a current plant using a green technique
$Q^{Green}_{ElecDem,fp\_Green}$	$\frac{kWh}{h}$	Green electricity consumed by the core technologies of the reference green future plant
$Q^{Blue}_{H2Dem}(cp)$ or $Q^{Green}_{H2Dem}(cp)$	$\frac{t_{H_2}}{h}$	H_2 consumed by a current plant using a blue/green technique
$Q^{Green}_{N2Dem}(cp)$	$\frac{t_{N_2}}{h}$	N_2 consumed by a current plant using a green technique
$Q^{Gray}_{NGDem}(cp)$ or $Q^{Blue}_{NGDem}(cp)$	$\frac{SCM}{h}$	Total natural gas consumed (for combustion and as feedstock) by a current plant using a gray/blue technique
Q_{NGDem,fp_Gray}	$\frac{SCM}{h}$	Total natural gas consumed (for combustion and as feedstock) by the reference gray future plant
$Q^{Gray}_{WaterDem}(cp)$ or $Q^{Blue}_{WaterDem}(cp)$ or $Q^{Green}_{WaterDem}(cp)$	$\frac{m^3}{h}$	Water consumed by the core technologies of a current plant using a gray/blue/green technique
$Q_{WaterDem,fp\_Gray}$ or $Q_{WaterDem,fp\_Green}$	$\frac{m^3}{h}$	Water consumed by the core technologies of the reference gray/green future plant
$Q_{ureaDemand}(t)$	$\frac{t_{urea}}{h}$	India's urea demand at a given hour t
t_a	years	Amortization time

1. Introduction

To address the threat of climate change, it is imperative to significantly reduce global greenhouse gas (GHG) emissions in all sectors, including industry. The production of synthetic nitrogenous (N-based) fertilizers, which played a pivotal role in catalyzing the "Green Revolution" during the 1960s, has increased sevenfold in the last fifty years (Ahmed et al., 2017). Consequently, the production and utilization of these fertilizers contribute significantly to global GHG emissions, accounting for approximately 5% of the total emissions (Gao and Cabrera Serrenho, 2023). The GHG emissions associated with the production and use of N-based fertilizers mainly consist of CO_2, N_2O, and CH_4 (Gao and Cabrera Serrenho, 2023). Among N-based fertilizers, urea is the most widely used, with an global production of approximately 184 million tons per annum [$\frac{Mt_{urea}}{a}$] (Statista Research Department, 2024a), representing 66% of all N-based fertilizers (Zhang et al., 2023).

India, which has the largest population in the world today (United Nations, Department of Economic and Social Affairs, 2023), is the second-largest producer of N-based fertilizers (Statista Research Department, 2023). Major fertilizers sold in India include urea, diammonium phosphate, and nitrogen-phosphorus (NP)/nitrogen-phosphorus-potassium (NPK), with urea alone accounting for 83% of the total fertilizer production in 2022–2023, in terms of nitrogen content (The Fertilizer Association of India, 2023). Note that many regions in India use fertilizers in excessive amounts, with an actual NPK application ratio of 11.8:4.6:1, which far exceeds the recommended average ratio of 4:1:1 for Indian agricultural lands (The Fertilizer Association of India, 2023). This overuse leads to environmental degradation by intensifying soil, atmosphere, and water pollution (Bora, 2022; Shukla et al., 2022). Apart from environmental damage, this overuse puts additional strain on state coffers because fertilizer sales are heavily subsidized in India, with a budget of approximately 22.8 billion USD for 2023–2024 (Government of India, 2024). Given that the fertilizer industry is the largest consumer of natural gas (NG) in the country (Statista Research Department, 2024b) and that India imported over 46% of its 2023–2024 natural gas consumption of 66.6 billion cubic meters (BCM) (Petroleum Planning and Analysis Cell, 2024), the NG-based production of most of these fertilizers increases the country's import bills (Nayak-Luke et al., 2022). As India seeks to reduce cumulative fossil fuel imports and GHG emissions under its National Hydrogen Mission (Ministry of New & Renewable Energy, 2023), the projected threefold increase in natural gas consumption by 2050 is a significant obstacle. This surge is expected to be primarily met by imported liquefied natural gas (LNG) (U.S. Energy Information Administration, 2024). Furthermore, the implementation of stringent international policies such as the EU's Carbon Border Adjustment Mechanism (CBAM), which aims to curb "carbon leakage" by importing carbon-intensive products such as fertilizers from non-EU countries, may further increase pressure on the fertilizer sector to decarbonize (European Commission, 2024). Given these challenges, decarbonization of urea production is critical for achieving India's sustainability goals and reducing its dependence on fossil fuels.

India currently has approximately 34[1] urea plants in operation (Department of Fertilizers, 2024b), all of which use natural gas as both fuel and feedstock (Singhal et al., 2023). Fig. 1 illustrates the individual and cumulative capacities of these plants (x-axis), arranged in descending order of plant age (primary y-axis). The width and color of each bar in the figure represent the capacity of a given plant, with the color highlighting historical trends in capacity development. Notably most of these plants are 30 years old or older, with seven surpassing 50 years of operation. With the exception of the two plants installed in 1985 and 1986 the largest plants, each with a capacity of 1.27 $\frac{Mt_{urea}}{a}$, have been constructed in recent years. In addition to capacity, the figure shows the CO_2 emission intensities of these plants in $\frac{t_{CO_2}}{t_{urea}}$ (secondary y-axis), estimated based on their reported or estimated natural gas consumption as fuel. Natural gas, which is used as a feedstock in the steam methane reforming (SMR) process, was excluded from these calculations, because it is integrated into the final product (urea) during urea synthesis. The

[1] Namrup-II and Namrup-III of BVFCL are not considered, as they were planned to be closed due to their low efficiencies (Department of Fertilizers, 2024b).

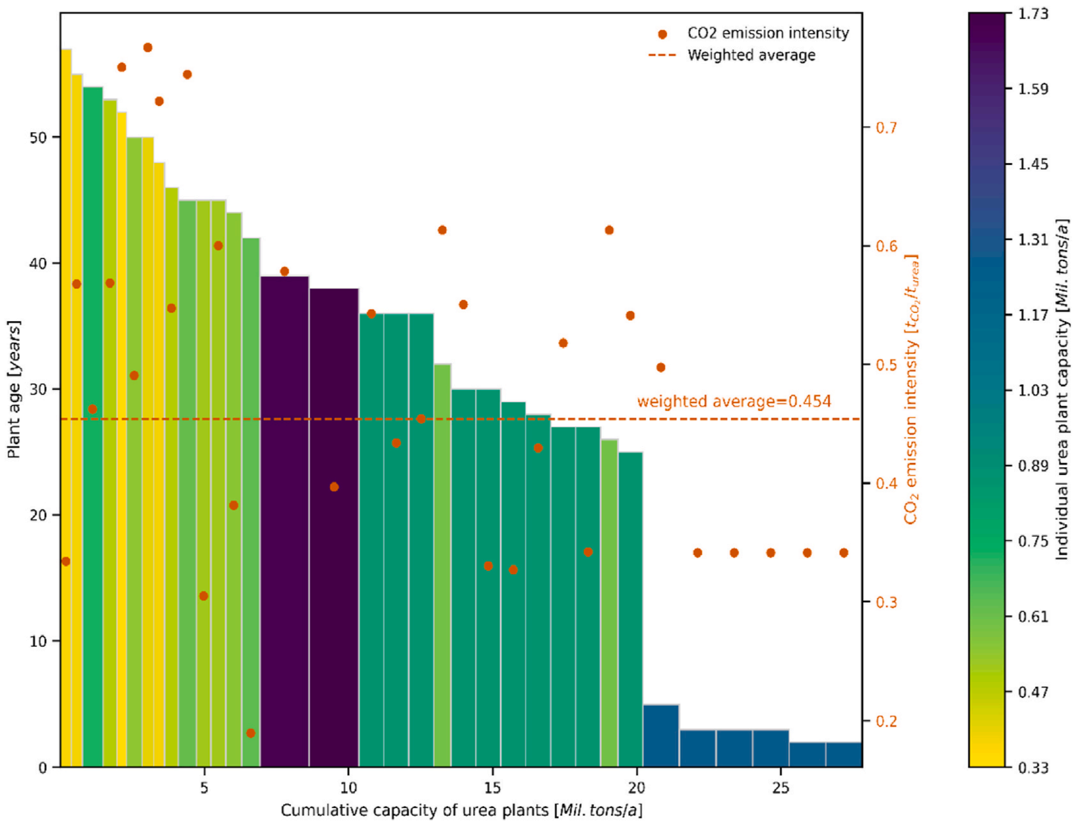

Fig. 1. Comparison of the CO_2 emission intensities (secondary y-axis) of India's 34 urea plants arranged in descending order of their age (primary y-axis).

newest plants exhibit some of the lowest CO_2 emission intensities, likely owing to improvements in process efficiency and electrification of previously steam-driven components. Notably, the lowest estimated CO_2 emission intensity (0.19 $\frac{t_{CO_2}}{t_{urea}}$), from the GNFC Bharuch plant, may be due to inaccuracies in reporting natural gas consumption or its allocation within the plant. The weighted average CO_2 intensity across all plants, based on individual plant capacities, is approximately 0.45 $\frac{t_{CO_2}}{t_{urea}}$, a value consistent with data for some of the current urea plants in India (Bhushan et al., 2019). Similarly, the weighted average natural gas consumption across these plants, including both fuel and feedstock, is approximately 645 standard cubic meter per ton of urea [$\frac{SCM}{t_{urea}}$]. **Figure B-3** in the appendix illustrates the water withdrawal intensities for these plants in $\frac{m^3}{t_{urea}}$, with a weighted average of 6.43 $\frac{m^3}{t_{urea}}$.

1.1. Literature review

A review of the literature on green urea production techniques revealed a steadily growing body of research, particularly focusing on techno-economic aspects. A study was conducted by Alfian and Purwanto (2019) employing multi-objective optimization to minimize the production costs and environmental impacts of green urea production by examining several alternative technologies for feedstock production. Their findings identified biomass gasification as the optimal technology for 2020–2035, whereas a combination of biomass gasification and photovoltaic (PV) electrolysis without battery storage was considered optimal for 2040–2050.

Several studies have focused on India's urea sector. Pawar et al. (2021) conducted a techno-economic analysis of renewable ammonia production in India using large-scale renewable parks. Nayak-Luke et al. (2022) adopted an island approach to identify price distortions in the coal and gas markets to estimate the relative costs of fossil fuel-based urea production. They concluded that green urea could become competitive with NG-based urea production by 2030, with a levelized cost of urea (LCOU) of 212 $\frac{USD}{t_{urea}}$ at the most favorable site. Kashyap et al. (2024) also conducted a techno-economic analysis focused on India, assessing the technical, environmental, and financial viability of deploying carbon capture and utilization (CCU) in Indian cement plants through multi-criteria analysis (MCA).

In another recent study, Khan et al. (2024) modeled a 0.46 $\frac{Mt_{urea}}{a}$ green urea plant using Aspen Plus and discounted cash flow analysis. They reported an LCOU of 710 $\frac{USD}{t_{urea}}$, identifying electrolysis and NH_3 synthesis as the most energy- and cost-intensive processes, respectively. Similarly, Devkota et al. (2024) performed a techno-economic assessment of a 0.22 $\frac{Mt_{urea}}{a}$ green urea plant powered by hydroelectricity and estimated an LCOU of 571 $\frac{USD}{t_{urea}}$ with a global warming potential of 326 $\frac{kg_{CO2}}{t_{urea}}$. They also found that carbon credits, that is, monetary compensation for offsetting CO_2 emissions, had a relatively insignificant impact on plant's return on investment (ROI) and payback period.

Palys and Daoutidis (2024) developed a techno-economic model that incorporated time-variable urea production to account for fluctuations in renewable energy availability. Using a minimum-cost-optimization approach, they estimated LCOUs ranging between 268 and 413 $\frac{USD}{t_{urea}}$, with an expected reduction to 135 $\frac{USD}{t_{urea}}$ by 2030, owing to advancements in technology and the expansion of electrolyzer manufacturing capacity.

In addition to techno-economic analyses, some studies have explored the technical aspects of green urea production in detail. Ishaq et al. (2021) evaluated the energetic and exergetic efficiencies of a hybrid system consisting of PV and wind energy with integrated units for CO_2 capture, air separation, ammonia, and urea synthesis. Milani et al. (2022) reviewed the various definitions of "green" urea in literature, highlighting instances where green urea is not entirely carbon-neutral. They also examined potential carbon-neutral CO_2 sources from an Australian perspective. Mao et al. (2024) conducted a quantitative analysis to assess the technical feasibility of green urea production, with a focus on system-wide efficiency.

This review highlights several gaps in the existing literature. Notably, there is a lack of comprehensive assessments of decarbonization measures across all urea plants in India, which could inform sectoral pathways to reduce emissions. Moreover, comparative analyses of current CO_2 and water withdrawal intensities, along with those projected after decarbonization measures, would offer valuable insights for policymakers and help set benchmarks for future green urea plants. Finally, detailed cost analyses of these pathways under different scenarios could elucidate the key challenges in transitioning to greener urea production methods.

1.2. Research questions

The main objective of this study was to address the identified research gaps by introducing a modeling approach for a comprehensive country-wide techno-economic analysis of existing and potential new urea plants. Using a central planner's perspective, we aimed to identify economically viable decarbonization pathways for India under different scenarios, specifically addressing the following research questions:

- What proportion of greener urea (blue/green) can be economically viable for India's urea production by 2050? Which factors could pose the most significant challenges to the sector's decarbonization efforts?
- How can the integration of these greener urea alternatives impact the sector's annual natural gas consumption along with its freshwater withdrawal intensity (measured in $\frac{m^3}{t_{urea}}$) and CO_2-emission intensity (measured in $\frac{t_{CO_2}}{t_{urea}}$)? Which scenarios are likely to result in the highest intensities in India?
- What are the main drivers influencing the cost of urea under different scenarios? How should the resulting urea costs be assessed in terms of their competitiveness in the international markets?

The model-based approach to addressing these questions provides new insights into the feasibility, environmental impacts, and cost implications of transitioning toward greener urea production in India as well as information for decision makers and stakeholders in the fertilizer industry. The remainder of this paper is structured as follows. Section 2 details the methodology used to model current and future urea plants. Section 3 presents and discusses the results. Finally, Section 4 presents concluding remarks and provides an outlook on future work.

2. Methods

This study was based on energy system modeling methods and adapted them to the modeling of the decarbonization pathways in urea plants. The modeling approach is described in detail in Section 2.1, and Sections 2.2 and 2.3 discuss the main input assumptions for the case study and scenarios, respectively. Finally, the techno-economic modeling of individual production plants and the demand and price projections are explained in **Appendices A and B**, respectively. Fig. 2 illustrates the information flow between these methods.

2.1. Modeling approach

The optimization model for this study was developed using the Renewable Energy Mix (REMix) energy modeling framework (Gils et al. 2017, 2021). REMix is a versatile framework for setting up linear optimization models, written in GAMS (DLR, 2024), and its modular structure allows the reuse of modeling concepts and the associated source code to address various energy system-related problems. Originally developed for energy system modeling, this framework is adapted and extended in this study to model the decarbonization pathways of India's gray urea plants under different scenarios. By leveraging the established structure and concepts of REMix, this study maintained the adaptability of the model for future research questions (DLR, 2024). Given the finite number of urea plants in India and the nature of the decisions involved (for example, whether to retrofit or replace plants), a mixed-integer linear programming (MILP) approach was employed.

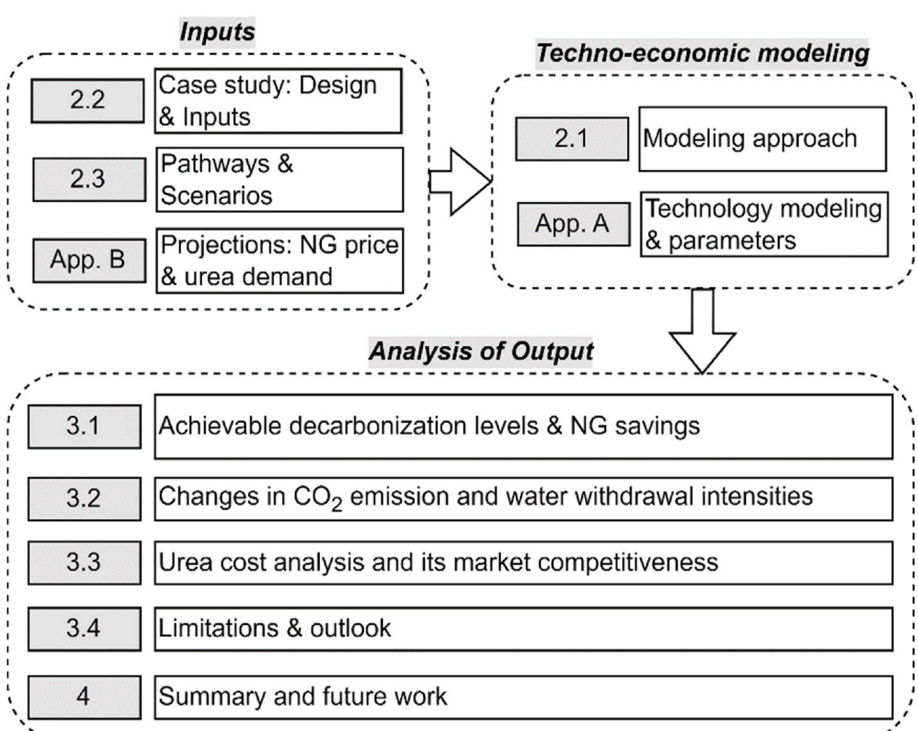

Fig. 2. Flowchart of the implemented methods. The numbers in the shaded box indicate the sections in which the details are provided.

2.1.1. Urea types

In the context of this study, the terms "gray," "blue," and "green" urea, indicating varying degrees of decarbonization, are defined as follows:

Gray urea: A typical NG-based urea plant comprising several sub-plants and technologies. However, for the modeling purpose, the umbrella term "core urea plant" is employed, comprising four sub-technologies: captive power plant (CPP), SMR, ammonia (NH_3) synthesis, and urea synthesis (Fig. 3). The SMR process has two outgoing streams of CO_2: i) CO_2 emissions generated by the combustion of natural gas as fuel, and ii) process CO_2 released as a by-product from a shift reaction after consuming natural gas as a feedstock. The process CO_2 is then fed into the urea synthesis section. Because the CO_2 produced during combustion is emitted into the atmosphere, the urea produced from such a plant is referred to as "gray" urea and the plant as a "gray" urea plant. The process design of the core urea plant determines the amount of natural gas consumed (generally expressed in $\frac{SCM}{t_{urea}}$) and freshwater withdrawn (measured in $\frac{m^3}{t_{urea}}$) to produce urea at a given hourly rate, while emitting a certain amount of CO_2 (measured in $\frac{t_{CO_2}}{t_{urea}}$) from the SMR and CPP technologies into the atmosphere.

Blue urea: To mitigate CO_2 emissions, the core urea plant can be retrofitted by adding in-house carbon capture technology to capture the CO_2 originally emitted by SMR and CPP technologies to be utilized as process CO_2 in urea synthesis process. This reduces the required amount of process CO_2 from the SMR process, resulting in lower natural gas consumption by the SMR and a reduction in synthesis gas production (H_2+N_2). The reduced amount of H_2 can be compensated by installing an electrolyzer, and the reduced amount of N_2 is assumed to be accommodated by controlling the air flow in the SMR process. The urea produced from such a plant is referred to as "blue" urea and the plant as a "blue" urea plant.

Green urea: By ensuring no fossil fuel consumption in the urea plant, urea production can be completely carbon neutral. This implies the non-use of fossil fuel-based technologies within the core urea plant, such as SMR and the CPP, if they are already installed. As an alternative, the syngas (H_2+N_2) required for NH_3 synthesis can be generated using an electrolyzer and a cryogenic air-separation unit (ASU) for its H_2 and N_2 components, respectively. Moreover, the process CO_2 necessary for urea synthesis must be sourced externally, for example, by capturing it at a nearby CO_2 source, such as a thermal power plant, iron and steel plant, or cement plant. The captured CO_2 must be compressed and then transported to the urea plant via a pipeline. The urea produced from such a plant is referred to as "green" urea and the plant as a "green" urea plant.

2.1.2. Current plants

The core urea plants that are already installed and operational are henceforth referred to as "current plants." At the time of this writing, all current plants in India are NG-based, that is, they employ the gray production technique. These plants can potentially be retrofitted to adopt blue or green production techniques, as described in the previous section. Within the model, each current plant has three possible pathways: it can either continue operating using the gray technique, be retrofitted to either the blue or green technique, considering the relevant process and cost assumptions (detailed in the following equations), or be decommissioned. However, capacity expansion of these plants is not permitted in this model.

The three possible production techniques are modeled as distinct "converter activities" within REMix, each associated with its own operating cost, which includes only the "non-energy costs" associated with the core urea technologies, because costs for natural gas and electricity are accounted for separately. These non-energy costs include employee salaries and welfare, maintenance and repairs, depreciation and amortization, financing costs, freight and handling, and other miscellaneous expenses (Singhal et al., 2023). Notably, based on the financial data of existing urea plants, these non-energy costs are assumed to be sufficient for the periodic replacement of worn-out equipment, thereby eliminating the need for decommissioning plants owing to reaching a predefined operational lifetime.

Note that the operational costs for green urea activity are proportionately reduced, as it utilizes only two of the four core technologies (namely, NH_3 synthesis and urea synthesis). These cost proportions are assumed to be the same as those applied to technology-level capital investments (detailed plant-level data are available via the link in Section Data availability). Moreover, operating a current plant using blue or green activities would necessitate the installation of new technologies, such as electrolyzers, with the cost calculations provided in Section 2.1.4.

The activity-based commodity conversion equations used for current plants are shown below, in which *cp* represents one of the 34 current urea plants in India ($cp \rightarrow CP$). In this study, *parameters* (values given as input to the model) are distinguished from ***variables*** (values calculated within the model), with the latter represented in bold. These are summarized in the nomenclature. The commodity conversion equations for gray, blue, and green urea activity are described in equations E1, E2, and E3, respectively.

$$\boldsymbol{Q}^{Gray}_{ureaProd}(t,cp) + \boldsymbol{Q}^{Gray}_{CO2Emission}(t,cp) = \boldsymbol{B}^{Gray}(t,cp) \bullet \left(Q^{Gray}_{NGDem}(cp) + Q^{Gray}_{WaterDem}(cp)\right) \ \forall t,cp \tag{E1}$$

$$\boldsymbol{Q}^{Blue}_{ureaProd}(t,cp) + \boldsymbol{Q}^{Blue}_{CO2Emission}(t,cp) = \boldsymbol{B}^{Blue}(t,cp) \bullet \left(Q^{Blue}_{NGDem}(cp) + Q^{Blue}_{WaterDem}(cp) + Q^{Blue}_{CO2Dem}(cp) + Q^{Blue}_{H2Dem}(cp)\right) \ \forall t,cp \tag{E2}$$

$$\boldsymbol{Q}^{Green}_{ureaProd}(t,cp) = \boldsymbol{B}^{Green}(t,cp) \bullet \left(Q^{Green}_{ElecDem}(cp) + Q^{Green}_{WaterDem}(cp) + Q^{Green}_{CO2Dem}(cp) + Q^{Green}_{H2Dem}(cp) + Q^{Green}_{N2Dem}(cp)\right) \forall t,cp \tag{E3}$$

Although the hourly rates of urea and CO_2 emission are plant-specific parameters, the above equations indicate them as variables based on the endogenously determined Boolean variable $\boldsymbol{B}(t, cp)$. Moreover, at a given time, a *cp* can produce these two commodities by using only one of the above three activity equations.

The maximum urea production from a given current plant at a given time is limited by the existing capacity of the plant:

$$\boldsymbol{Q}_{ureaProd}(t,cp) \le Cap(cp) \ \forall t,cp \tag{E4}$$

where $\boldsymbol{Q}_{ureaProd}(t,cp)$ represents the sum of urea production using the three techniques (Equations (E1)–(E3)).

The annual non-energy operating costs of all activities of all current plants are computed using Equation (E5). Although these costs are typically fixed annual costs, they are modeled as variable operating costs in the case of current plants to individually account for the costs of each of the three modeled activities. Moreover, no investment costs are considered for core technologies, because capacity expansion of current plants is not permitted.

$$\boldsymbol{C}_{OMVar,CP} = \sum_{cp}^{CP}\sum_{t}^{T=8760}\boldsymbol{Q}^{Gray}_{ureaProd}(t,cp) \bullet c^{Gray}_{OMVar}(cp) + \sum_{cp}^{CP} \times \sum_{t}^{T=8760}\boldsymbol{Q}^{Blue}_{ureaProd}(t,cp) \bullet c^{Blue}_{OMVar}(cp) + \sum_{cp}^{CP}\sum_{t}^{T=8760}\boldsymbol{Q}^{Green}_{ureaProd}(t,cp) \bullet c^{Green}_{OMVar}(cp) \tag{E5}$$

2.1.3. Future plants

Any urea demand left unfulfilled by the aforementioned current plants can be satisfied by installing new urea plants, which are henceforth referred to as future plants. Based on the type of technology installed, each of these future plants can be either gray or green urea future plants (*fp_Gray* or *fp_Green*, respectively). The blue urea tech-

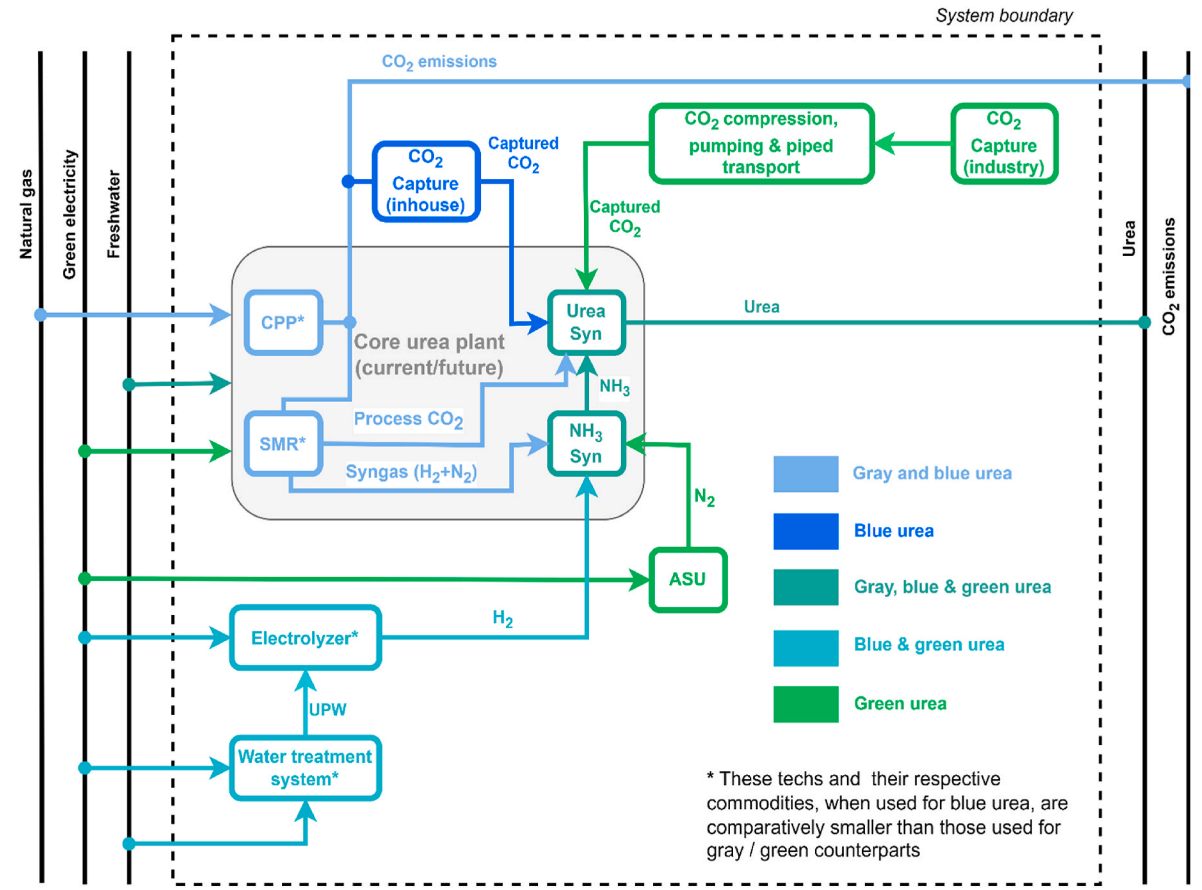

Fig. 3. Simplified process flow diagram of a typical gray core urea plant (current or future plant) along with the technologies necessary to convert it into a blue/green production technique. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

nique is excluded in this case, as it is treated as a transitional technique only for current plants. Moreover, the modeling approach of future plants differs from that of current plants, in that all future plants are modeled to operate using a single activity (i.e., gray or green). In the case of current plants, each plant can operate with one of the three possible activities (i.e., gray, blue, and green). Furthermore, unlike current plants where each plant can have a different capacity $Cap(cp)$, a single reference installable plant capacity (Cap_{fp}) is chosen for all gray and green future plants based on the most prevalent plant capacity in recent years. As such, any unfulfilled urea demand can be addressed by installing one or multiple units of this reference future plant ($\boldsymbol{N}^{T^*}_{FP\_Gray}$ and $\boldsymbol{N}^{T^*}_{FP\_Green}$) based on the gray and green techniques, respectively. The conversion equations for the core technologies of future urea plants (gray and green) are given in Equations E6 and E7, respectively:

$$\boldsymbol{Q}_{ureaProd,FP\_Gray}(t) + \boldsymbol{Q}_{CO2Emission,FP\_Gray}(t) = \boldsymbol{N}^{O^*}_{FP\_Gray}(t) \bullet \left(Q_{NGDem,fp\_Gray} + Q_{WaterDem,fp\_Gray}\right) \ \forall t \quad \text{(E6)}$$

$$\boldsymbol{Q}_{ureaProd,FP\_Green}(t) = \boldsymbol{N}^{O^*}_{FP\_Green}(t) \bullet \left(Q_{ElecDem,fp\_Green} + Q_{WaterDem,fp\_Green} + Q_{CO2Dem,fp\_Green} + Q_{H2Dem,fp\_Green} + Q_{N2Dem,fp\_Green}\right) \ \forall t \quad \text{(E7)}$$

The maximum urea production is limited by the number of future plants installed:

$$\boldsymbol{Q}_{ureaProd,FP\_Gray}(t) \le \boldsymbol{N}^{T^*}_{FP\_Gray} \bullet Cap_{fp} \ \forall t \quad \text{(E8)}$$

$$\boldsymbol{Q}_{ureaProd,FP\_Green}(t) \le \boldsymbol{N}^{T^*}_{FP\_Green} \bullet Cap_{fp} \ \forall t \quad \text{(E9)}$$

The installation of a future plant results in capital and operating expenditures; those of its core technologies are computed as follows:

$$\boldsymbol{C}_{invest,FP} = \left(\boldsymbol{N}^{T^*}_{FP\_Gray} \bullet c_{specInv,fp\_Gray} + \boldsymbol{N}^{T^*}_{FP\_Green} \bullet c_{specInv,fp\_Green}\right) \bullet f_{annuity} \quad \text{(E10)}$$

$$f_{annuity} = \frac{i \bullet (1+i)^{t_a}}{(1+i)^{t_a} - 1} \quad \text{(E11)}$$

$$\boldsymbol{C}_{OMFix,FP} = \boldsymbol{C}_{invest,FP} \bullet c_{OMFix,fp} \quad \text{(E12)}$$

where $f_{annuity}$ is the annuity used to annualize the capital investment.

2.1.4. Other technologies

The associated costs for the installation of all technologies (*other_techs*) other than the aforementioned core urea technologies, unless otherwise mentioned, are computed using the equations below. Note that $c_{specInv,other\_techs}$ must be computed for each urea plant based on the required capacity of that technology.

$$\boldsymbol{C}_{invest,other\_techs} = \boldsymbol{N}^{T^*}_{other\_techs} \bullet c_{specInv,other\_techs} \bullet f_{annuity} \ \forall other\_techs \quad \text{(E13)}$$

$$\boldsymbol{C}_{OMFix,other\_techs} = \boldsymbol{C}_{invest,other\_techs} \bullet c_{OMFix,other\_techs} \ \forall other\_techs \quad \text{(E14)}$$

2.1.5. Urea balance

The urea balance below ensures that demand is met at all times while also ensuring system stability by exporting any additionally produced quantity.

$$Q_{ureaDemand}(t) = \sum_{cp}^{CP} \boldsymbol{Q}_{ureaProd}(t, cp) + \boldsymbol{Q}_{ureaProd,FP\_Gray}(t) + \boldsymbol{Q}_{ureaProd,FP\_Green}(t) + \boldsymbol{Q}_{ureaImport}(t) - \boldsymbol{Q}_{ureaExport}(t) \ \forall t \tag{E15}$$

2.1.6. Objective function for optimization

This study employed a MILP approach to allow discrete installation and decommissioning decisions for urea plants. Using perfect foresight over the optimization horizon and a central planner's perspective on urea production for the entire country, cost-minimizing modeling was performed. The objective function for optimizing the overall system cost over the entire time horizon is as follows:

$$min\left\{ \boldsymbol{C}_{invest,FP} + \boldsymbol{C}_{OMFix,FP} + \boldsymbol{C}_{OMVar,CP} + \sum_{other\_techs} \left(\boldsymbol{C}_{invest,other\_techs} + \boldsymbol{C}_{OMFix,other\_techs}\right) + \boldsymbol{C}_{importNG} + \boldsymbol{C}_{importWater} + \boldsymbol{C}_{importElec} + \boldsymbol{C}_{CO2Emission} + \boldsymbol{C}_{CO2Capture} + \boldsymbol{C}_{import} - \boldsymbol{R}_{export} \right\} \tag{E16}$$

where $\boldsymbol{C}_{importNG}$, $\boldsymbol{C}_{importWater}$, $\boldsymbol{C}_{importElec}$, and $\boldsymbol{C}_{import}$ are costs incurred for importing natural gas, freshwater, grid electricity, and urea, respectively. $\boldsymbol{C}_{CO2Emission}$ is the cost resulting from the carbon tax for emitting CO_2 from urea plants, whereas $\boldsymbol{C}_{CO2Capture}$ is the cost of capturing CO_2 (either within the plant, as in the case of blue urea, or from an external CO_2 source, as in the case of green urea). $\boldsymbol{R}_{export}$ is the revenue generated from urea export.

2.1.7. Levelized cost of urea (LCOU)

To enable a cost comparison of urea with the literature, the LCOU was calculated once the model had calculated a cost-optimal system to meet the given urea demand. It was determined by dividing the overall system cost by the net urea production (from all current and future plants) over the entire time horizon.

$$LCOU = \frac{\sum_{t=0}^{T=8760*opt.years} overall\ system\ cost}{\sum_{t=0}^{T=8760*opt.years}\left(\sum_{cp}^{CP}\boldsymbol{Q}_{ureaProd}(t,cp) + \boldsymbol{Q}_{ureaProd,GrayFp}(t) + \boldsymbol{Q}_{ureaProd,GreenFp}(t)\right)} \tag{E17}$$

2.2. Case study: design & inputs

This study evaluated all 34 urea plants currently operating in India[2] (Department of Fertilizers, 2024b). However, to simplify the model while capturing the key characteristics, the plants were grouped based on similar capacities and ages, resulting in 12 plant groups. The optimization was conducted for the period 2026–2050, with 2026 chosen to account for the time required to plan and implement retrofitting measures for decarbonization. All current plants are allowed to remain in operation during the entire optimization period, regardless of their age or condition, with plant decommissioning treated as an endogenous, cost-based decision within the model. The operating costs of each plant were obtained from the annual financial reports of the companies that owned and operated the plants. Because financial data are often reported at the company level and each company usually operates multiple facilities, the operating costs for individual plants are estimated based on the amount of urea produced at each facility. The process flow and relevant financial data were compiled in this study, whereas data on freshwater source and specific water consumption for all plants were obtained from Narain et al., 2019. Further information on individual plants and modeled plant groups can be found in the Supplementary Data (see **Data availability**).

For new urea plants, the most prevalent capacity for recently installed facilities in India is 1.27 $\frac{Mt_{urea}}{a}$, with HURL Sindri being one of the most recently commissioned facilities (Department of Fertilizers, 2023). Hence, this plant was chosen as a benchmark for future gray urea plant installations in terms of process efficiency and installation cost (refer **Appendix A.1**). In the case of green urea plants, two additional technologies were considered: an electric steam generator (to superheat the steam from NH_3 synthesis to the conditions necessary for urea synthesis) and a switchyard (owing to the use of high-voltage components, such as an electrolyzer).

The annual projections for natural gas costs and urea demand in India are detailed in **Appendices B.1 and B.2**, respectively. The results and discussion in this study were based on the "iFOREST optimal" scenario of urea demand forecast (see **Figure B-2**), unless otherwise specified. To model the hourly urea demand profile, an annual plant availability of 330 days was assumed, with demand distributed evenly across the first 330 days of each year and no demand for the remaining days. Regarding the urea trade assumptions, no urea imports were considered over the entire optimization horizon, aligning with India's goal of achieving self-sufficiency in urea production by 2025 (Business Today, 2022). However, based on historical trade data, the model allowed for annual urea exports of up to 5% of annual demand. A constant export revenue of 450 $\frac{USD}{t_{urea}}$ was assumed for all years (Fertiliser India, 2021).

In India, distribution companies and large consumers can procure electricity through round-the-clock (RTC) tenders via standardized, long-term power purchase agreements (Gulia et al., 2021). Recent renewable-plus-storage RTC tenders have varied from 0.0957 to 0.04 (for peak and off-peak power, respectively) to 0.0496 $\frac{USD_{2026}}{kWh_{el}}$ (Gulia et al., 2021; Saurabh, 2020; Shetty, 2023). In this study, a constant tariff of 0.0575 $\frac{USD_{2026}}{kWh_{el}}$ was assumed for the entire optimization period. The other relevant parameters for the case study are as follows:

- Freshwater withdrawal from all urea plants originates from a natural water source (surface/groundwater) at no additional cost
- Discount rate i of 10.6% (considering a debt-to-equity ratio of 70:30, with 12% return on equity and 10% interest on loans (Singhal et al., 2023))
- Amortization period t_a for new investments of 25 years
- All actual costs are extrapolated to 2026 using interest rates of 3% and 4% for the capital and operating costs, respectively (Singhal et al., 2023)
- All costs are expressed in USD_{2026}

[2] Namrup-II and Namrup-III of BVFCL are not considered, as their closure is planned due to their low efficiencies (Department of Fertilizers, 2024b).

2.3. Pathway and scenario definition

India currently produces 100% of its urea using the gray production technique, which is likely to continue in the foreseeable future. Therefore, it is essential to compare the impact of decarbonization measures against the backdrop of current fossil fuel-based urea production. The following two pathways were defined:

- ***Business-as-usual (BAU) pathway:*** This pathway permits urea production using only the gray techniques of current and future urea plants. The retrofitting of current plants or the installation of future green urea plants is not permitted. However, the model allows for the decommissioning of operating plants to reduce the overall system costs.
- ***Decarbonization pathway:*** This pathway allows for urea production using all three techniques (gray, blue, and green) to meet the given urea demand while minimizing system costs.

To account for uncertainties in the numerous techno-economic assumptions underlying the model, we assessed the potential impact of varying key parameters on the calculated LCOU and the achievable level of decarbonization. Consequently, the two pathways were investigated using the following six scenarios:

- ***Base scenario:*** This serves as the reference scenario, incorporating the techno-economic assumptions detailed in Section 2.2. The following are the variations in this scenario, with only the specified variations applied at a time, unless otherwise noted.
- ***Higher NG cost:*** This scenario examines the implications of increased natural gas prices, which constitute approximately 80% of the operating costs of urea plants in India. The assumptions for higher natural gas prices are based on the "low economic growth" scenario of US Henry Hub price projections, elaborated further in **Appendix B.1**.
- ***Lower NG cost:*** Conversely, this scenario explores the potential challenges posed by lower natural gas prices, which can hinder decarbonization efforts. The "high oil and gas supply" scenario of US Henry Hub price projections is utilized to assess this impact, as elaborated in **Appendix B.1**.
- ***Lower NG cost and carbon tax:*** To mitigate the potential negative impact of lower natural gas price projections on decarbonization efforts, climate policies, such as carbon taxes on CO_2 emissions or regulatory measures, can be implemented. Regulatory measures can include mandatory CO_2 emission intensity targets for the sector. If these targets are not met, the plant operators are required to purchase certified carbon credits through a trading exchange (Bureau of Energy Efficiency, 2024). In this study, a carbon tax was chosen as the preferred policy mechanism, as regulatory policies are found to be costlier and lead to greater competitiveness losses, particularly in heterogeneous, energy-intensive trade-exposed (EITE) sectors (Chateau et al., 2024). Although India has not yet explicitly introduced a carbon tax (OECD, 2022), the political challenges of implementing such a policy are known (International Monetary Fund, 2023). Therefore, this study assumed a relatively modest carbon tax of 50 $\frac{USD}{t_{CO2}}$ starting in 2030, which is lower than the carbon prices observed in the EU's emission trading system (EU-ETS) (International Carbon Action Partnership, 2024). This tax was further raised to 100 $\frac{USD}{t_{CO2}}$ for 2040, extending through the remaining period of optimization. The natural gas price projections remained the same as those in the aforementioned scenario with a lower natural gas cost.
- ***Higher electrolyzer cost:*** Although alkaline electrolyzers are an established technology, their installation costs have increased notably due to inflation (International Energy Agency, 2023). This scenario evaluates the consequences of elevated electrolyzer costs by assuming the upper limit of the specific cost range (see **Appendix A.2**) in comparison with the mean value considered in other scenarios (International Energy Agency, 2019).
- ***Higher electricity cost:*** In contrast to gray urea plants, where natural gas is the main operating cost component, the operational cost of a green urea plant is likely to be dominated by electricity costs. This scenario assumes a 20% higher cost for electricity than the base scenario, reflecting the fluctuations in renewable electricity prices observed in past RTC tenders in India.

These pathways and scenarios facilitate a comprehensive analysis of the possible pathways for the sector and the impact of key economic conditions and policy implementations on the LCOU and decarbonization potential of India's urea production sector.

3. Results and discussion

This section is organized into three parts, each addressing one of the research questions outlined in Section 1.2. Section 3.1 examines possible natural gas savings and achievable decarbonization levels for India's urea production. Section 3.2 analyzes the water and CO_2 emission intensities of urea production for the two pathways under various scenarios. Finally, Section 3.3 discusses the costs associated with urea production and its market competitiveness. The output data files used to generate the resulting graphs are available via the link provided in the **Data availability** section.

3.1. Large natural gas savings and high level of decarbonization under most scenarios

Fig. 4 illustrates the Indian urea sector's projected annual natural gas consumption [$\frac{BCM}{a}$] and the associated specific CO_2 emissions [$\frac{Mt_{CO2}}{BCM}$] for 2050 for the BAU and decarbonization pathways under various scenarios. The depicted values were derived from the model results by summing them across all current and future urea plants in India for 2050, irrespective of the production technique in individual plants. CO_2 emissions are shown in relation to natural gas consumption to assess the impact of different scenarios on the sector's technology choice.

As shown, except for the scenario with lower natural gas cost, natural gas consumption in the decarbonization pathway was significantly lower under all scenarios. Conversely, natural gas consumption and associated CO_2 emissions remained unchanged for the BAU pathway under all scenarios (approximately 11 $\frac{BCM}{a}$ and 0.8 $\frac{Mt_{CO2}}{BCM}$, respectively). On the other hand, the decarbonization pathway indicated a significantly lower fossil fuel consumption and associated CO_2 emission intensity.

In the decarbonization pathway, the natural gas consumption in the base scenario fell below 0.5 $\frac{BCM}{a}$, whereas it reached zero in the scenario with high natural gas costs. This effect can be explained by the high share of green urea (>93%) in these scenarios, as shown in **Figure C-1** in the **Appendix**. Based on the urea demand forecast of 18.2 $\frac{Mt_{urea}}{a}$ for 2050 (see **Figure B-2**), this would entail a natural gas consumption intensity of merely 24 $\frac{SCM}{t_{urea}}$ for the base scenario in 2050, indicating a decrease of 96% from the sector's current weighted average of 645 $\frac{SCM}{t_{urea}}$. Conversely, lower natural gas costs lead to the highest natural gas consumption (>10 $\frac{BCM}{a}$) observed in this pathway, which was associated with an 80% share of gray urea (see **Figure C-1**). This scenario also tended to be the most CO_2 intensive (>0.64 $\frac{Mt_{CO2}}{BCM}$) for this pathway, indicating a preference for continued operation with inefficient and/or gray urea technologies. However, implementing a CO_2 tax in this case indicated not only a strong 64% decrease in this fossil-energy-intensive trend, but also a shift toward less CO_2-intensive technologies, as indicated by a 47% reduction in emitted CO_2 per unit of natural gas consumed. In this case, the share of gray urea dropped below 14%. While the values in scenarios with

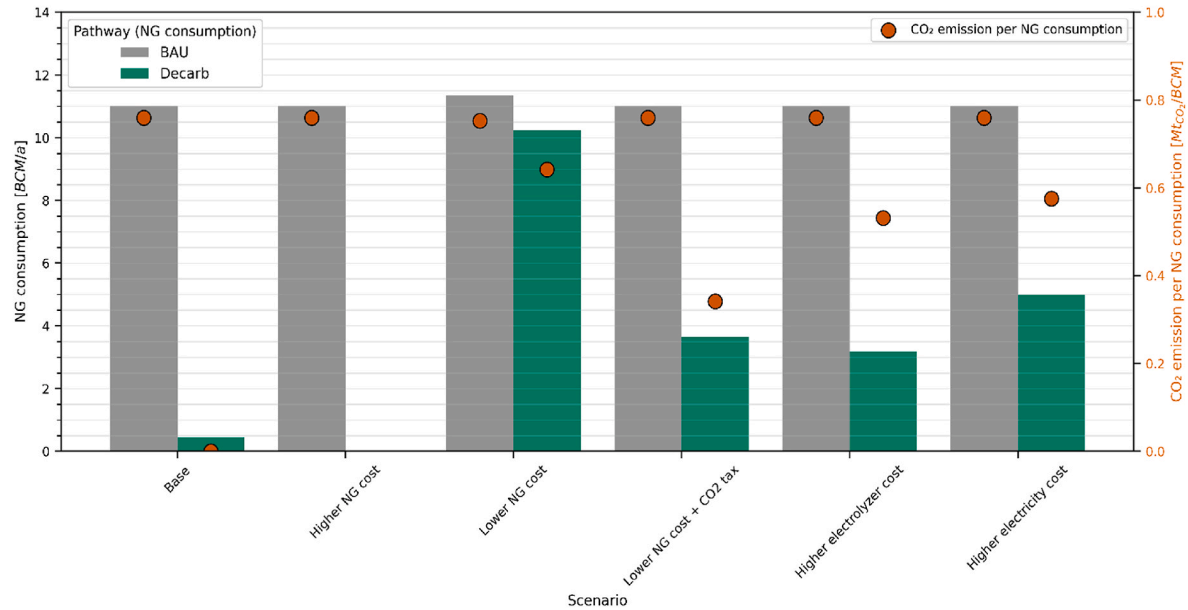

Fig. 4. Annual natural gas consumption (bar plot, primary y-axis) and CO_2 emissions per BCM of natural gas consumed (scatter plot, secondary y-axis) in 2050 for the BAU and decarbonization pathways under different scenarios. The urea demand forecast used in the calculation is based on iFOREST's optimal scenario.

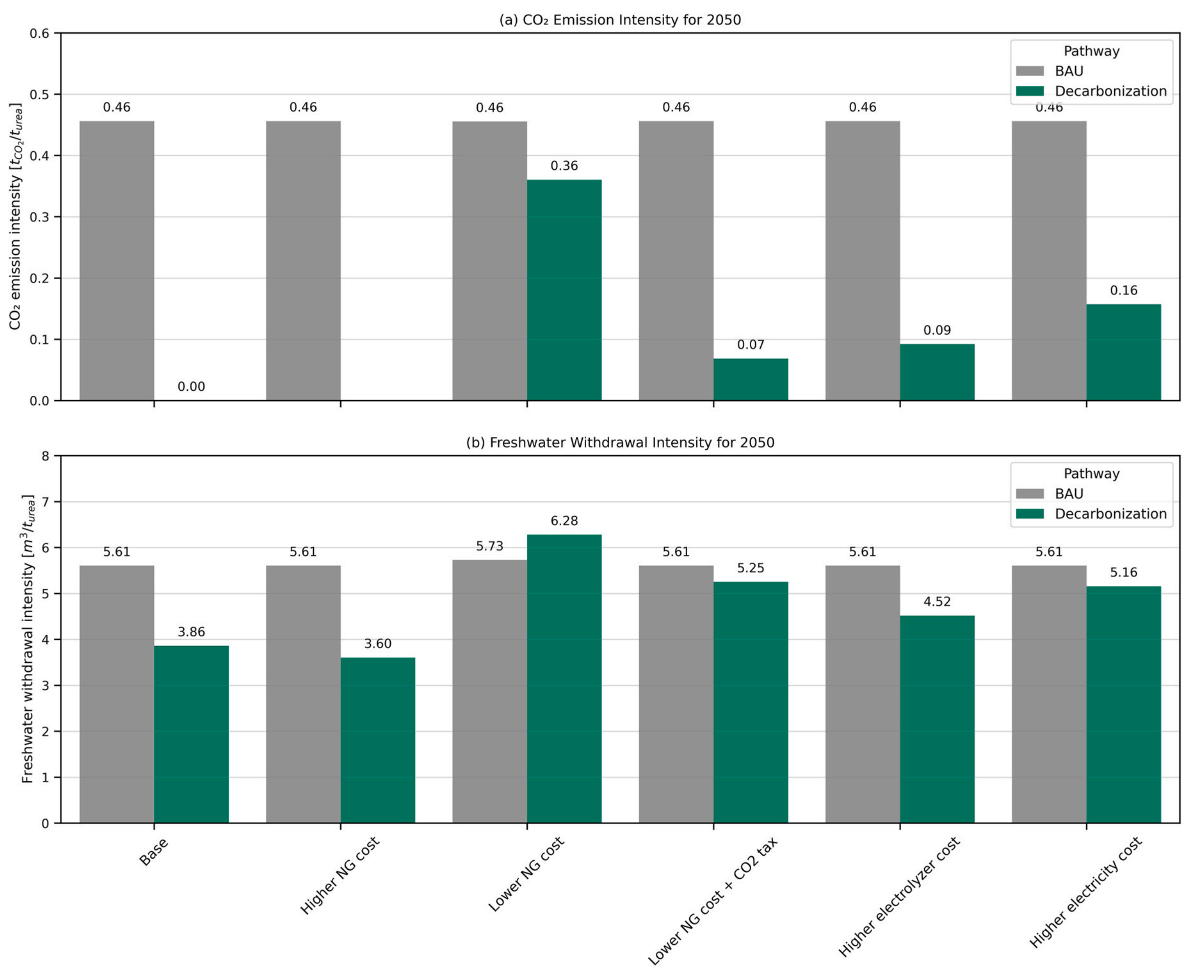

Fig. 5. (a) Projected CO_2 intensity (top) and (b) freshwater withdrawal intensity (bottom) in 2050 for the BAU and decarbonization pathways under different scenarios. The urea demand forecast used in the calculation is based on iFOREST's optimal scenario.

higher electrolyzer and electricity costs were comparable to those with a lower natural gas cost + CO_2 tax, they remained significantly natural gas- and CO_2-intensive compared with the base scenario.

Overall, in terms of natural gas consumption and CO_2 emissions, the results indicate a relative inelasticity of the BAU pathway to the modeled scenarios. The decarbonization pathway revealed a strong inclination to reduce natural gas consumption and CO_2 emissions, except in the case of lower natural gas costs.

3.2. Lower CO_2 emissions and water consumption

Fig. 5 presents two vertically aligned plots depicting the projected CO_2 intensity (top) $[\frac{t_{CO_2}}{t_{urea}}]$ and freshwater withdrawal intensity (bottom) $[\frac{m^3}{t_{urea}}]$ for 2050 for the BAU and decarbonization pathways under various scenarios.

The analysis indicated that the CO_2 and freshwater withdrawal intensities in the BAU pathway (at 0.46 $\frac{t_{CO_2}}{t_{urea}}$ and 5.61 $\frac{m^3}{t_{urea}}$) remained largely unaffected by the modeled scenarios; however, they were highly elastic in the decarbonization pathway. The water withdrawal intensities in the decarbonization pathway were lower than their BAU counterparts in almost all scenarios. They were noticeably higher when the electrolyzer and electricity prices were higher than those in the base scenario. The lower water intensities observed at high decarbonization levels were primarily driven by the increasing share of green urea production, which does not involve the SMR process, thus sparing the additional water required for non-process activities, such as heating and cooling, utility, and domestic consumption (see **Table A-1**). Moreover, the water intensity in the base scenario (at 3.86 $\frac{m^3}{t_{urea}}$) was 40% lower than the current national average (see **Figure B- 3**). Consequently, for a projected urea demand of 18.2 Mt_{urea} by 2050, this shift to decarbonization could lead to an annual water saving of approximately 47 million m^3.

The CO_2 intensity of urea production under the decarbonization pathway was near zero for all scenarios, except when natural gas costs were lower, in which case it was 0.36 $\frac{t_{CO_2}}{t_{urea}}$. Implementing a CO_2 tax would lead to an 80% reduction in urea's CO_2 intensity and a 16% reduction in freshwater intensity. In the case of the base scenario, a 100% reduction in the CO_2 intensity by 2050 from the current national average of 0.45

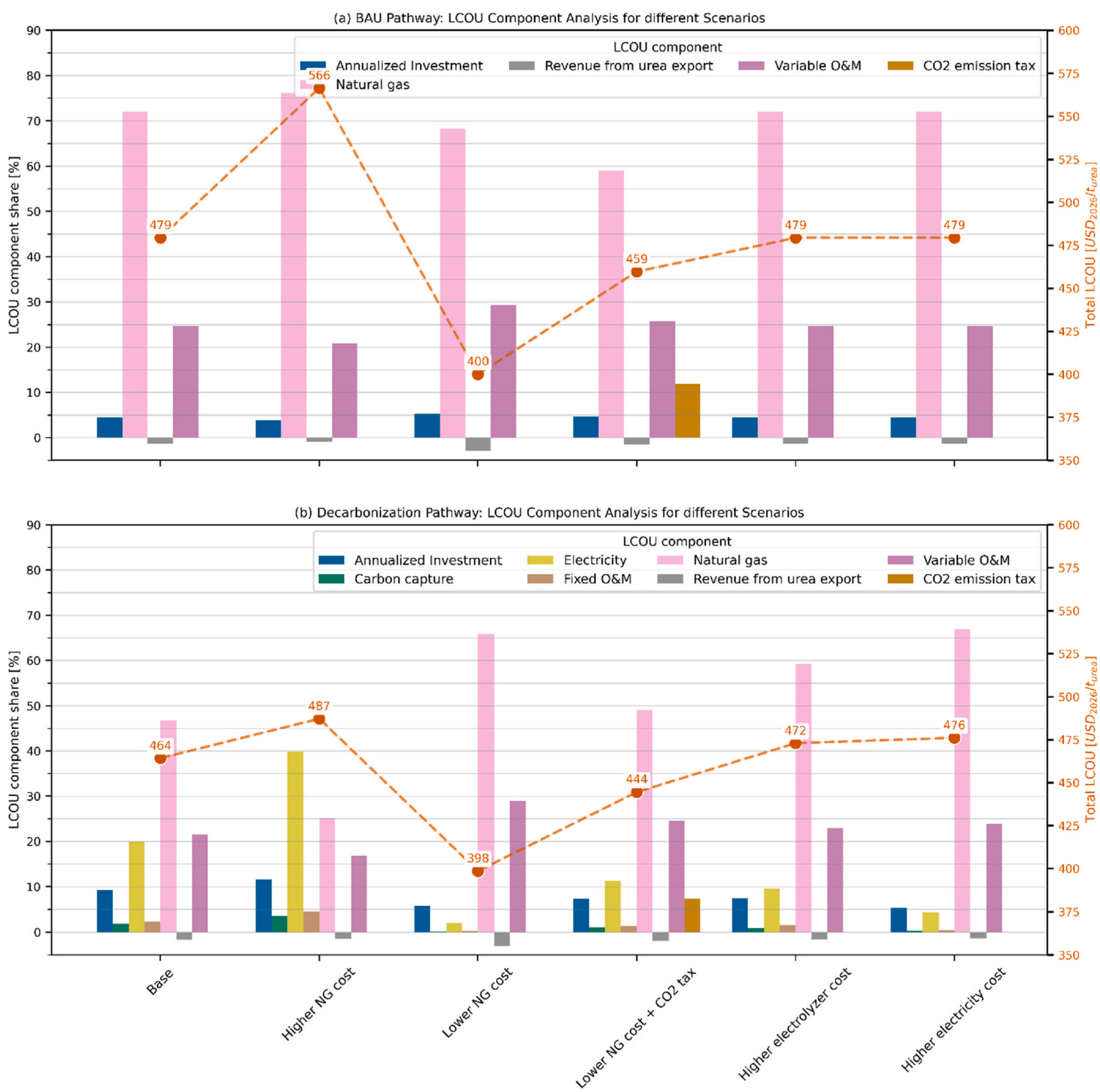

Fig. 6. Total LCOU over the optimization horizon as scatter plot (secondary y-axis) and its sub-components as a bar plot (primary y-axis) under different scenarios for the (a) BAU pathway (top), and (b) decarbonization pathway (bottom). The urea demand forecast used in the calculation is based on iFOREST's optimal scenario.

$\frac{t_{CO_2}}{t_{urea}}$ implies an annual avoidance of 8.19 Mt_{CO2}, based on the projected urea demand.

Overall, in terms of CO_2 emission and water withdrawal intensities, the BAU pathway was inflexible in different scenarios and had higher intensities. The decarbonization pathway, with lower CO_2 and water footprints, showed a significant positive impact of the CO_2 tax policy.

3.3. LCOU: decarbonization provides robustness against market fluctuations

Fig. 6 illustrates the total estimated LCOU for the two pathways under different scenarios and their sub-component shares. The secondary y-axis shows the total LCOU $[\frac{USD_{2026}}{t_{urea}}]$ as a scatter plot, whereas the primary y-axis represents the share of each LCOU component as % of the total LCOU in a bar plot.

The results revealed a higher share of natural gas costs within the LCOUs of the BAU pathway compared to the decarbonization pathway, resulting in greater variability in BAU pathway's total LCOUs in NG-based scenarios. While the decarbonization pathway's base-scenario LCOU were only 3% lower than that in the BAU pathway, this difference grew to over 16% when natural gas costs were high. Across scenarios, the proportion of LCOU components in the BAU pathway remained relatively stable.

In the BAU pathway, natural gas expenditure was the dominant cost factor, accounting for over 75% of the LCOU when natural gas prices were high. Conversely, in the decarbonization pathway for the same high-natural gas-cost scenario, the fossil fuel's share in the LCOU was reduced to 25%, showcasing the decarbonization pathway's resilience to natural gas price surges. When natural gas costs were low, its share in the LCOU increased to over 65%, yet remained lower than that in the BAU pathway. Implementing a CO_2 tax raised the LCOUs under both pathways, although it being comparatively modest in the decarbonization pathway (11.5% vs 15% in the BAU pathway), further highlighting this pathway's adaptability to external cost pressures. Similarly, higher costs for electrolyzers and electricity led only to a modest increase in LCOU in the decarbonization pathway, while maintaining its diversified cost structure.

Overall, the LCOUs under the BAU pathway exhibited high sensitivity to natural gas price fluctuations, leading to substantial variance (4,742 vs 1,030 $\left(\frac{USD_{2026}}{t_{urea}}\right)^2$ in the decarbonization pathway) and reflecting greater risks and uncertainties. By contrast, the decarbonization pathway demonstrated a more stable cost structure, offering resilience against market fluctuations and mitigating exposure to fuel price volatility and regulatory shifts.

Although investment costs in the decarbonization pathway constituted a relatively small fraction of the LCOU (less than 10% under most scenarios), a detailed analysis was considered essential to assess the relative cost significance of different decarbonization technologies. Fig. 7 presents a bar chart illustrating the percentage share of different technologies in the total investment costs for each scenario (primary y-axis); their total value (in billion USD_{2026}) is shown on the secondary y-axis. The investment costs for the gray and green variants of future urea plant installations are presented separately. The BAU pathway was excluded from this analysis because its installation costs comprised only future gray urea plants.

The analysis revealed that future gray urea plants dominated investment costs in most scenarios, contributing between 50 and 93%, except under conditions of high natural gas costs when no investment was allocated for new fossil fuel-based plants. This trend suggests the model's preference for replacing some of the existing energy-intensive urea plants with future gray urea plants, which are more energy-efficient (see **Appendix A.1**). Conversely, future green urea plants represented less than 0.6% of the total investment in most scenarios, with the exception of the high natural gas cost scenario, where their share increased to 18%. This pattern highlights a strong dependence on retrofitting existing gray urea plants with either blue or green urea production techniques to achieve high levels of decarbonization by 2050, as outlined in Section 3.1. Notably, the investment share of the water treatment system remained negligible across all scenarios, averaging only 0.3%, underscoring its minimal contribution to the LCOU.

In the base scenario, electrolyzers accounted for approximately 40% of the investment, with the total investment in technologies required for green urea production representing approximately 50%. Given the negligible investment in future green urea plants under the two scenarios, these green technologies were predominantly installed in existing plants that were retrofitted.

In contrast, under conditions of lower natural gas costs, a majority of the investment costs (nearly 93%) was directed toward new gray urea plants. The imposition of a CO_2 tax reduced this share to 66%. Similarly,

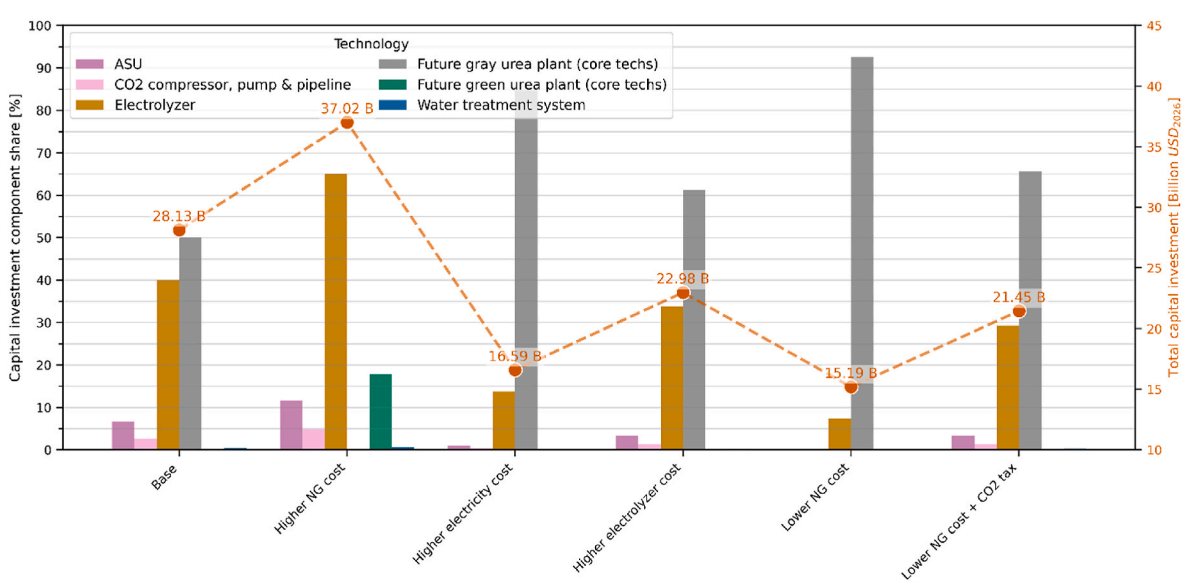

Fig. 7. Investment costs under the decarbonization pathway over the entire optimization horizon: percentage share of technologies (primary y-axis) and the total value (secondary y-axis) under different scenarios. The urea demand forecast used in the calculation is based on iFOREST's optimal scenario.

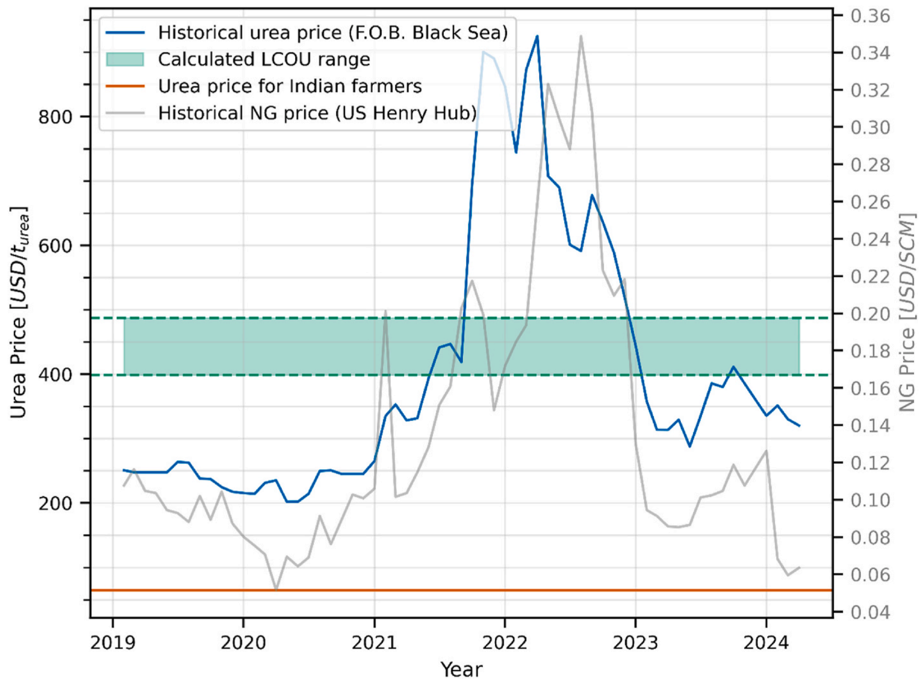

Fig. 8. Comparison of historical urea prices (F.O.B. spot prices in the Black Sea) (Index Mundi, 2024b), calculated LCOU range under the decarbonization pathway, and subsidized urea price for Indian farmers (all on the primary y-axis) with the historical natural gas prices (spot prices at US Henry Hub) (Index Mundi, 2024a) on the secondary y-axis. The urea demand forecast used in the calculation is based on iFOREST's optimal scenario.

higher electricity costs induced a comparable investment pattern, favoring gray urea plants.

In summary, investments in new gray plants dominated most scenarios, with significant decarbonization primarily achieved through the retrofitting of existing urea plants in India.

To assess the competitiveness of the urea produced under the modeled decarbonization scenarios, they were compared with historical urea prices, as shown in Fig. 8. The primary y-axis $[\frac{USD}{t_{urea}}]$ shows the historical urea spot F.O.B. prices in the Black Sea (Index Mundi, 2024b) (in blue, for the period from February 2019 to April 2024). The figure also shows the range of LCOU calculated in this study (shown in green) and the subsidized urea prices for Indian farmers (in red), which have remained constant since 2018 at 268 INR for a bag of 50 kg (Department of Fertilizers, 2024a), translating to approximately 65 $\frac{USD}{t_{urea}}$. The secondary y-axis shows the historical spot prices for natural gas (at the Henry Hub) in $\frac{USD}{SCM}$ (gray, for the period from February 2019 to April 2024) (Index Mundi, 2024a). The natural gas prices were converted from $\frac{USD}{MMBTu}$ to USD per standard cubic meter of natural gas or $\frac{USD}{SCM}$, using a net caloric value of 10000 $\frac{kCal}{SCM}$ and 252000 $\frac{kCal}{MMBTu}$ (Petroleum Planning & Analysis Cell, 2021).

A strong positive correlation of 0.766 was observed when historical urea and natural gas prices were compared. Because natural gas costs currently account for approximately 80% of the operational costs of natural gas-based urea plants in India, this strong correlation suggests a similarly high share of natural gas in the operating costs of traded urea. The anomalous behavior between mid of 2021–2022, when the price increase in urea preceded that of natural gas, is noteworthy. Moreover, a strong fluctuation was observed in historic urea prices, varying between 202 and 925 $\frac{USD}{t_{urea}}$, in the observed period.

Comparing the calculated LCOUs in the modeled scenarios with the historical urea prices, we found that the calculated LCOUs were cheaper for a period of approximately 19 months, from 2021 to early 2023. This cost advantage could be attributed to the high natural gas prices during this period. However, from the beginning of 2023, the price of traded urea has declined, reaching 334 $\frac{USD}{t_{urea}}$ in the first quarter of 2024, although it has not yet returned to the low levels observed from 2019 to 2021. Regardless, the prices paid by Indian farmers remain heavily subsidized and unaffected by these fluctuations.

Overall, it can be said that the cost competitiveness of calculated LCOUs depends strongly on natural gas prices. However, the values in Figs. 8 and 6 (top, BAU pathway) also demonstrate the cost risk of current urea production owing to natural gas price fluctuations, leading to an increase in the financial burden on government expenditure in the form of urea subsidies, when natural gas prices rise. While reducing this burden, decarbonization measures can also help save foreign currency, as the country imports nearly half of its NG needs (International Energy Agency, 2024).

3.4. Limitations and outlook

This study introduced a novel approach to evaluate the decarbonization versus BAU pathways for urea plants as part of a larger, country-level system. However, following limitations provide opportunities for future research to improve the reliability of the results and broaden the applicability of the model.

3.4.1. Cost assumptions

Modeling over long-time horizons (up to 2050) inherently involves uncertainties in cost assumptions. Notably, the price volatility of NG, driven by recent geopolitical events, introduces significant uncertainty into the model results, given that natural gas constitutes a substantial share of the operating costs of current NG-based urea plants. Additionally, recent increases in electrolyzer costs (see Section 2.4) exacerbate these uncertainties. Although this study attempted to address these issues by modeling various scenarios, further research incorporating statistical probability into the results would be beneficial.

Some of the components necessary for decarbonizing urea plants, such as the switchyard and electric steam generator, are parameterized based on expert opinions and are highly simplified. Furthermore, it was assumed that the requirement for an ASU in a retrofitted blue urea plant could be eliminated through adjustments in the SMR process, which might not fully reflect the technical complexities. Moreover, fertilizer plants in India often produce multiple products, albeit in much smaller quantities, aside from urea, such as bio-fertilizers and bentonite sulfur. Therefore, the assumed natural gas consumption and financial data that are currently allocated solely to urea production must be examined more closely. Combined with other process and cost assumptions, these aspects require further refinement in future studies.

3.4.2. Modeling assumptions

The current model configuration does not impose mandatory decommissioning timelines on existing plants based on their operational lifetimes. Instead, it assumes that periodic maintenance, funded through a portion of the non-energy costs, will allow these plants to remain operational through the optimization horizon. Given these assumptions, the model demonstrates a strong preference for retrofitting existing plants to minimize overall system costs rather than constructing new green urea plants. While this approach will enable significant decarbonization by 2050 under most scenarios, it would be optimistic to expect the oldest urea plants in India, most of which are over 30 years old, with seven exceeding 50 years, to remain operational until 2050. This assumption underscores the potential limitations of the model and highlights the need for more nuanced decommissioning strategies in future studies.

The optimization method applied to 34 urea plants was based on a central planner's perspective. However, given the unique interests and autonomy of each plant owner/operator, implementing decarbonization solutions derived from such a top-down methodology may prove challenging without regulatory intervention. Therefore, future research should explore individualized decarbonization strategies for each plant. Moreover, rather than assuming an RTC-based constant renewable electricity supply, modeling renewable technologies, such as PV and wind, combined with storage technologies, such as batteries and hydrogen storage, could enable the analysis of individual plants in off-grid scenarios.

Typically, an existing urea plant is retrofitted from gray to either blue or green urea, but not vice versa. However, in the model, the gray, blue, and green production techniques for a current plant are modeled as "activities" so that a plant can switch from green/blue activity back to gray activity if it deems it economically feasible. Although this may be technically possible, it would not be implemented in practice. Thus, the method should be further refined to allow only "forward transformation" of activities: from gray to blue or green.

This study modeled technologies with the goal of meeting urea demand only. However, this method can be extended by modeling the technologies necessary to produce other fertilizers, which could potentially serve as more environmentally friendly substitutes for urea. Modeling the demand and technologies for extracting, storing, and transporting hydrogen and ammonia, which are considered energy carriers for a decarbonized economy, can further enhance the applicability of this model.

Overall, this approach offers a valuable model-based assessment of the decarbonization pathways for urea production, with potential usefulness for policymakers and researchers. It also presents opportunities for the improvement and extension of this approach to other industrial transformation processes.

4. Summary and future work

Using a cost-optimizing approach from a central planning perspective, this study assessed and compared key indicators for BAU and decarbonization pathways for India's NG-based urea production over the period 2026–2050 under various scenarios. This was achieved by building a techno-economic model that captured data from India's 34 urea plants and the technologies necessary for decarbonization (electrolyzers, carbon capture, ASUs, etc.) and integrating them into the REMix energy system framework. A key scientific contribution of this study is the demonstration of how retrofitting measures for existing plants can be represented as "converter activities" within an energy modeling framework such as REMix. Each of the existing gray urea plants was modeled with the potential for retrofitting to either blue or green urea technology or to be decommissioned and replaced with new gray or green urea plants. The model inputs included projections for natural gas costs and urea demand until 2050.

The results revealed a strong preference toward the decarbonization of India's urea production, with the base scenario indicating 93% green urea by 2050, resulting in a 96% decrease in natural gas consumption intensity from the current sectoral average of 645 $\frac{SCM}{t_{urea}}$. This was accompanied by a 40% decrease in freshwater withdrawal intensity from the current sectoral average of 6.43 $\frac{m^3}{t_{urea}}$. This was largely driven by the increasing adoption of green urea production, which eliminated the water-intensive requirements of the conventional SMR process. Lower NG costs revealed a major hurdle in decarbonizing urea, with approximately 80% of urea remaining gray until 2050 in the corresponding scenario. This challenge could be almost entirely mitigated by implementing a carbon tax, reducing the share of gray urea to 14% by 2050. Under this pathway, urea's average CO_2 intensity will decrease from the current 0.45 $\frac{t_{CO_2}}{t_{urea}}$ to nearly CO_2-free urea production by 2050, whereas it will remain unchanged for the BAU pathway.

In terms of LCOU, although the base scenario of the decarbonization pathway suggested only a modestly lower LCOU of 464 $\frac{USD_{2026}}{t_{urea}}$ compared to the BAU pathway, the values were relatively stable across scenarios, highlighting the robustness of the pathway under different market conditions. The cost competitiveness of the LCOU in international markets was closely tied to natural gas price fluctuations. For example, during the periods of elevated natural gas prices from 2021 to early 2023, largely driven by geopolitical tensions, the LCOU became more competitive.

In future work, we recommend exploring environmentally friendly alternatives to urea and integrating hydrogen and ammonia into the model as additional demand and end products, given their expected significance in a carbon-neutral future. Additionally, integrating life cycle assessments could provide a more comprehensive perspective on the pathways for decarbonizing not only the nitrogen fertilizer sector, but also a broader energy system, offering deeper insights into the environmental impacts of various technologies and decarbonization measures.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Nikhil Dilip Pawar: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Kunal Singhal:** Resources, Project administration, Investigation, Data curation. **Chandra Bhushan:** Supervision, Project administration, Funding acquisition. **Thomas Pregger:** Writing – review & editing, Supervision, Funding acquisition. **Patrick Jochem:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nikhil Dilip Pawar reports financial support was provided by

Sustainability Innovations and Advisories (SIA) Pvt. Ltd. Kunal Singhal reports a relationship with International Forum for Environmental Sustainability & Technology (iFOREST) that includes: employment. Chandra Bhushan reports a relationship with International Forum for Environmental Sustainability & Technology (iFOREST) that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.144433.

Data availability

The Appendix along with other data files are openly accessible at Mendeley Data, doi: 10.17632/4r22hy4hnr.3

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