Special Issue on The End Game: How to Achieve Carbon Neutrality

# Assessing the Viability of Decarbonising India's Nitrogenous Fertiliser Consumption

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The fertiliser sector in India is essential to its economy and for its food security. Despite being the second largest global producer of fertilisers, substantial imports of raw materials and fertilisers are required to bridge the demand gap for N-P-K fertilisers in India. Islanded green ammonia production in India shows significant potential to provide a carbon-free source of nitrogen for fertiliser production that will reduce India's imports of both nitrogenous fertilisers and the raw materials required for its production. Green ammonia production also carries many socioeconomic benefits compared to conventional production, such as enhanced job creation, reduced feedstock importation and air pollution. Using an existing islanded green ammonia production model, and applying it across India at a 1.0° (110.6km) resolution using ERA5 (European Centre for Medium-Range Weather Forecasts Reanalysis 5th Generation) solar irradiance, windspeed and temperature data as an input. A heatmap of the achievable levelized cost of ammonia (LCOA) is then created, identifying areas which show strong potential for green ammonia production. Three scenarios for the levelised cost of electricity (LCOE) reduction are considered and a more detailed analysis is performed on five locations of particular economic and social interest. These results are then used as the present value of ammonia to benchmark the cost of islanded production of 'green urea' against conventional means. The major price distortions in the Indian coal and gas markets are identified and stripped out to compare the relative costs of urea production. By 2030, urea produced from green ammonia can be cost-competitive with urea produced from natural gas and even coal with a modest price of carbon and when fossil-fuel price distortions are stripped out.

## 1. Introduction

Nitrogen is one of the three key nutrients needed for plant growth, alongside phosphorus and potassium. It is the most important primary nutrient, accounting for 57% of nutrient consumption [2]. The Haber-Bosch process, developed in the first decade of the 20th Century by Fritz Haber and Carl Bosch, revolutionised modern agriculture by providing an industrial process to convert hydrogen and nitrogen into ammonia. This process is the main source of nitrogen for fertilisers and approximately 50% of the world's food production relies on ammonia-based fertilisers [3]. Ammonia is mainly used as an intermediate material for fertiliser production, with direct application making up only 4% of global consumption of nitrogen fertilisers[2]. It is predominantly used to make urea (50% of global consumption) or ammonium nitrate (14% of global consumption) but is also used to make complex fertilisers that contain two or more of the three key nutrients.

The current dependence on fossil fuels in the production of ammonia not only as the hydrogen feedstock but also for primary energy means that ammonia production accounts for approximately 420M tonnes of $CO_2$ emissions annually, over 1% of global energy-related emissions [4]. Substituting the use of fossil fuels for hydrogen and energy with zero-carbon sources, such as solar photovoltaics (PV) or wind-fuelled electrolysis, has great potential to provide ammonia at a fraction of the carbon footprint. Green ammonia also shows potential as a store of hydrogen, so called 'Power-to-X' [5], which would assist with renewable energy integration into the grid. Research is also exploring its potential to be used as a fuel directly, most notably in shipping [6] which predicts that a green ammonia production capacity comparable to the global total today will be required by 2035, increasing to 400-500% of today's total capacity by 2050 [7]. This is predicted to require USD 1-1.9T.

This paper performs a detailed techno-economic analysis of green ammonia production across the entirety of India. Focusing on five locations for economic, societal, and political reasons, specifically those with the lowest LCOA, proximity to significant variable renewable energy (VRE) deployment, proximity to old existing capacity, and proximity to where coal gasification is being considered, green urea production has been compared in detail against conventional production and predicted to be economically competitive without support before 2028. This paper initially provides context of India's ammonia supply & demand, outlines the methodology used, calculations performed and key results. To conclude the implications of these results are discussed, the limitations of the analysis outlined, and the key conclusions summarised. This research has identified green urea production as a promising technology to decarbonise India's fertilizer sector whilst continuing to provide sufficient food security. Previous investigations (analysed in detail in Supplementary Material, Note 2) examining green production of ammonia have not examined India (excluding Pawar et al. (2021) [63]) and have looked at ammonia as a traded commodity, rather than as an intermediary material for nitrogenous fertilisers on site which makes up its primary consumption [2]. Production of urea from green ammonia is not widely examined in the literature, but Alfian and Purwanto (2019)[55] provided an optimisation model that considered the future development of technologies and feedstock prices from 2020-2050 to minimize production costs and environmental impacts. Biomass gasification was found to be the optimum during 2020-2035, while combined biomass-PV electrolysis without battery technology was identified as the optimum technology from 2040-2050. Driver et al (2019)[30] examined the chemical synthesis of urea via a synthetic route reported in Barzagli et al. (2011) [56] with comparatively mild conditions compared to the Bosch-Meiser process. Combining this process with hydrogen produced from renewable-powered electrolysis could produce a urea fertilizer with reduced energetic, financial and environmental costs, referred to as “*Blue Urea”*, which would only require inputs of air, water and externally captured $CO_2$. However, this was strictly a chemical exploration of production with no economic costings. Geographically the closest literature to this paper is Pawar et al. (2021) [63] who considered India’s potential for green ammonia production without considering the existing distortions in India’s market. They concluded that 822-870 USD/$t_{NH3}$ is the currently achievable LCOA and is thereby uncompetitive against conventional production. However, this study did not consider future cost of electricity or key processes such as the electrolyser and assumed large areas were used for power generation instead of using the best resources in a dedicated way.

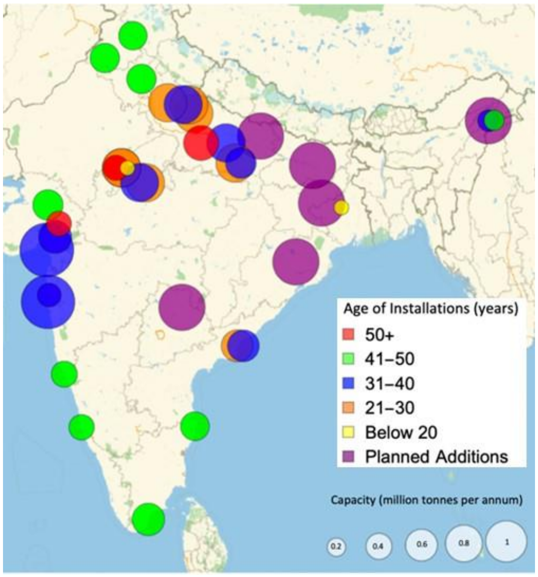

Figure 1: Distribution and age of current domestic capacity in India

## India – an agricultural hub

India is the second largest global consumer of fertilisers, with a total of 25.95m tonnes of consumption in 2016, with 17.4m tonnes of nitrogenous fertilisers alone [2]. The chemicals and fertilizer sector accounts for nearly 12% of India’s manufacturing sector’s greenhouse gas emissions, the third largest sector after power and steel [8], and Indian agriculture accounts for over 7% of global agricultural emissions [9].

India has a rapidly growing population, with future projections estimating that India will overtake China by 2027 to become the most populous country in the world [10]. Food grain production in India has increased fivefold over the last half a century, from 53Mt p.a. in 1951-52 to 252.22Mt p.a. in 2015-16 [11]. Chemical fertilisers have played an integral role in this expansion [11] and India is significantly dependent on the industry for its food security. Agriculture also accounts for approximately 1/7th of India’s GDP and 42% of its total employment [12] making fertilisers an essential sector of India’s economy. The importance of fertiliser will grow as India’s population rises and as crop yields fall due to climate change. Urea is the world’s most used nitrogen fertiliser, making up 48% of the global nitrogen fertiliser consumption by nutrient composition [13]. It is especially popular in developing countries, as it has the highest nitrogen content (46%) of all solid nitrogenous fertilisers and thereby the cheapest form to transport [2].

The Government of India classifies fertilizers as an “essential” commodity, with their availability and distribution controlled by the Department of Agriculture, Cooperation and Farmers Welfare [11]. The industry is heavily subsidised, with payments accounting for nearly 0.6% of GDP and 2.6% of the Government of India’s Budget[14]. The price of urea (the dominant fertiliser in India[2]) is strictly controlled through a maximum retail price at nearly a third of global market prices. This intervention provides a low price to farmers that is shielded from global price fluctuations. The difference between the cost of production and maximum retail price is provided as a subsidy to urea manufacturers by the Government [11], reaching nearly 70% of the cost of production [15].

India’s domestic nitrogenous fertiliser production capacity is substantial, with 31 ammonia-urea fertiliser plants across the country [11], and two ammonia plants that are not integrated with urea production[18]. The current capacity, as shown in Figure 1, is also relatively old, at an average age of 34 years [16]. Despite the additional five units announced, significant investment will be required in the near future to either extend the lifetime of current plants or to replace them. Arguably the most notable of these units is the Talcher installation in the state of Odisha which will be back in operation by 2023. This plant will be based on coal gasification technology [22], a cheaper but more environmentally damaging production pathway for ammonia which is dominant in China [23].

While the current domestic capacity predominantly uses natural gas, the lack of domestic natural gas allocated to the industry has left it relying on costly imported re-liquefied natural gas (R-LNG) for 58% of its supply, mainly from Qatar [19]. A pooling system that ensures a weighted average price regardless of source was implemented in 2015 to smooth over the impact on the cost of production and reduce the government’s subsidy bill. The variable cost of the gas feedstock makes up the most significant portion of the production costs of urea, at nearly 90% of total cost of production [2]. A minor fluctuation in natural gas prices can significantly increase the subsidy burden to the government.

From this brief overview, several problems can be identified: reliance on imports of raw materials and fertilisers, domestic capacity reaching the end of its lifetime, further capital investments for energy efficiency measures, and distortions caused by government intervention. Previous studies [1] have identified India as showing promising potential for islanded green ammonia production, due to its substantial renewable energy resources [24]. With the problems faced by the industry, exploring the potential in India for green ammonia production is essential to advise governmental policy and the industry's decisions in the coming decades. This research utilises and refines the model, initially outlined in [28] and refined in [1], to assess the potential for green ammonia in India based on wind and solar ERA5 (European Centre for Medium-Range Weather Forecasts Reanalysis 5th Generation) Land data.

Comparisons are then made with urea production from natural gas and coal to compare its cost parity, with the aim of identifying sites which hold strong potential to compete with carbon-intensive fertilizer production in the near future. Distortions in the cost of conventional production are also assessed and quantified before inclusion in the analysis, with particular examination of the distortions in the pricing of Indian coal and natural gas. A case for green urea is then made, based on its competitiveness and the socioeconomic benefits associated with sustainable production.

## 2. Methodology

This research uses ERA5 Land data at a granularity of 1.0° (110.6km) downloaded from [29] with the model outlined in [1] to develop a heatmap of the achievable levelized costs of ammonia (LCOA) in India. A summary of this model's methodology, the technical / economic assumptions used for this study, and a review of its reliability can be found in Supplementary Material, Notes 1 and 2. It considers an islanded production process which is powered by renewable sources of energy (wind and solar photovoltaic) to synthesise hydrogen from water electrolysis and nitrogen from air separation. The products are then combined to create ammonia via the Haber-Bosch process.

To manage the intermittent supply inherent with renewable energy sources, a hydrogen buffer is incorporated to smooth the supply of hydrogen and (if necessary) energy to the reaction processes during low power periods. To determine the lowest achievable LCOA for each location, as in [1] a genetic algorithm is used to optimise three variables; the rated power of the electrolyser, the combined rated power of the HB and ASU, and the fraction of energy supplied by wind (with the remaining proportion sourced from solar PV).

Urea production is typically integrated on site with an ammonia plant, with 94% of the ammonia plants in India being located alongside a urea plant. Carbon dioxide and ammonia are required for urea production through the Bosch-Meiser process (5)-(6). These are both readily available onsite as by-products of the ammonia production process, with $CO_2$ produced from hydrocarbon reforming. A description of the chemical processes involved in urea production is included below (Equations 4-6), with the natural gas, coal gasification and electrolytic hydrogen production pathways (Equations 1, 2 and 3 respectively).[30]

$$\mathrm{CH_4} + \mathrm{H_20} \rightleftharpoons \mathrm{CO} + 3\,\mathrm{H_2} \quad \Delta H = +206kJmol^{-1} \; (1)$$

$$\mathrm{CO} + \mathrm{H_2O} \rightleftharpoons \mathrm{CO_2} + \mathrm{H_2} \quad \Delta H = -41kJmol^{-1} \; (2)$$

$$\mathrm{H_2O} \rightleftharpoons \mathrm{H_2} + \frac{1}{2}\mathrm{O_2} \quad \Delta H = +286kJmol^{-1} \; (3)$$

$$3\mathrm{H_2} + \mathrm{N_2} \rightleftharpoons 2\mathrm{NH_3} \;\; \Delta H = -92kJmol^{-1} \; (4)$$

$$2\mathrm{NH_3} + \mathrm{CO_2} \rightleftharpoons \mathrm{NH_2COONH_4} \;\; \Delta H = -117kJmol^{-1} \; (5)$$

$$\mathrm{NH_2COONH_4} \rightleftharpoons \mathrm{CO(NH_2)_2} + \mathrm{H_2O} \;\; \Delta H = +15.5kJmol^{-1} \; (6)$$

In order to compare the cost of green urea to the current cost of production, a MATLAB function was created that uses capital expenditure estimates, specific consumption of $CO_2$ and ammonia from the Talcher production site [22] and energy intensity data from [31] to estimate the levelized cost of urea (LCOU) from Equation 7. These figures are detailed in Supplementary Material, Note 3. This installation was chosen as a basis for capital expenditure (CAPEX) costing as it is likely that in the future green urea production will have to compete with urea produced from a coal feedstock in India due to its relative low cost compared to other sites using alternative feedstock [22, 16] and India's significant domestic coal reserves [24].

$$\mathrm{LCOU} = \frac{\sum_{t=0}^{T} \dfrac{\mathrm{CAPEX_t} + \mathrm{OPEX_t} + \mathrm{m_C} \cdot \mathrm{p}_C + \mathrm{m_A} \cdot \mathrm{p_A}}{(1+\mathrm{r})^{\mathrm{t}}}}{\sum_{t=0}^{T} \dfrac{\mathrm{m_{Urea}}}{(1+\mathrm{r})^{\mathrm{t}}}} \quad (7)$$

This MATLAB function took the levelized cost of ammonia and electricity from the heat map created with ERA5 Land data and the model from [1] as their present costs and was subject to the same assumptions, detailed in Supplementary Material, Note 4. The resulting LCOU was then linearly interpolated between the 2019 and 2030 scenarios and compared to the conventional cost of production to estimate the year at which green urea will be competitive. The average of the current costs of installed capacity [16] was taken as a benchmark cost for steam reforming and the projected cost of production for Talcher [22] as a benchmark for coal gasification.

The function also had the cost of the carbon feedstock as an input, as carbon dioxide will no longer be produced on site. This also allows for comparison with scenarios including a carbon tax. The carbon intensity of the coal and natural gas production routes was taken from [32], at 3.0 and 1.9 of $CO_2t/tNH_3$ produced.

A literature review was also conducted, to identify and quantify distortions in the coal and natural gas markets in India. The most easily quantifiable distortions were identified (listed in Supplementary Material, Note 3) and applied to the costs of production identified in [22] and [16] to obtain the costs of production without distortions. These were then benchmarked against the cost of green urea from the MATLAB function.

## 3. Calculations

ERA5 data was used for the period 1990-2019 with hourly temporal resolution and 1 degree (110.6km) spatial resolution. Tranches of five-years of data (i.e. 1990-1994, 1995-1999…) were selected as they are a good representation of longer time periods at the locations considered and significantly reduced the simulation duration.

The 100m wind data was used and adapted to the hub height (80m) using Equation 8 before being converted to power using the Vestas 3.0MW turbine power profile with a cut-in speed of 4 m/s, cut-out speed of 25 m/s and an air density of 1.225 kg/m. When compared against historical wind power data and wind energy maps this was found to be significantly more representative of the available wind power than using the 10m data. The other technical and economic assumptions were in line with those in [1] and can be seen in Supplementary Material, Note 1.

$$U_1 = U_2 \left( \frac{\ln \frac{H_1}{z}}{\ln \frac{H_2}{z}} \right) \qquad (8)$$

Given the significant impact that the levelised cost of electricity (LCOE) has on the achievable LCOA, plant design and operation, and its considerable uncertainty we ran three scenarios which we have names for the purposes of clarity: achievable, optimistic and very optimistic. The very optimistic is calculated using 2019 installed CAPEX estimates and using the IRENA data to predict the compound annual growth rate (CAGR) to 2030 (see Supplementary Material, Note 1). Despite the very high R-values, India has some of the lowest LCOE spot prices for wind but particularly solar PV. In light of this, we set the optimistic and achievable to be 75% and 50% of this calculated CAGR so that we could identify the impact that the rate of LCOE reduction to 2030 has on the viability of green ammonia / urea. The 2019-2030 CAGR for wind in the achievable, optimistic and very optimistic scenarios was therefore -4.9% -3.7% and -2.5% respectively, and for solar PV -9.6%, -7.2% and -4.8%. The impact that this had on the LCOE and LCOA for the optimised systems is shown in Supplementary Material, Note 5.

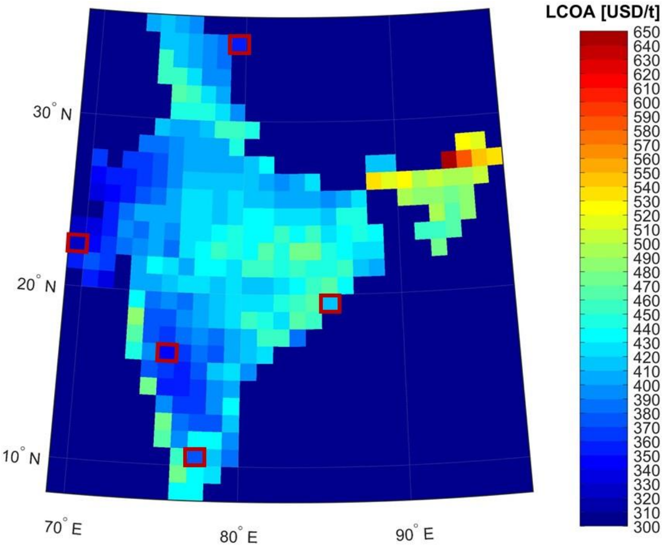

Figure 2: Achievable LCOE Scenario – Heat-map of green ammonia production of India and identifying five sites of interest (highlighted with white dashed boxes)

Having found the LCOA heatmap (Figure 2) for each scenario we identified five locations of particular interest to consider in greater depth using the "achievable" scenario. These locations (shown in Table 1) were selected as they had promising LCOA estimates, were spread geographically across India and had one additional key defining feature. Only five locations were selected as this provided the coverage required of the key features and spatially. The first as the lowest LCOA predicted and relative proximity to existing infrastructure is considerable national importance (specifically the Hajira-Bijapur-Jagdishpur natural gas pipeline). The second, due to the strong track-record of VRE deployment and available resource. The third and fourth, due to available land and proximity to significant fertiliser demand centres (such as Punjab, Tamil Nadu and Andhra Pradesh). The fourth also having the potential of capitalising of additional revenue streams from providing ammonia for international shipping fuel as this sector decarbonises. The final location was considered due to its proximity to the Thalcher production plant that is based on coal gasification and additional socio-economic benefits that such a development would bring. These results were used in combination with assessment of the Government of India's existing support for natural gas and coal based production to benchmark urea production and identify when green production will be competitive.

| Index | State | Longitude [°] | Latitude [°] |
|---|---|---|---|
| 1 | Gujurat | 69.5 | 23.0 |
| 2 | Maharashtra | 75.5 | 17.0 |
| 3 | Disputed | 79.5 | 35.0 |
| 4 | Tamil Nadu | 77.5 | 11.0 |
| 5 | Odisha | 85.5 | 20.0 |

Table 1: The five locations of particular interest to considered in greater depth using the "achievable" scenario.

## 4. Results

The attainable LCOA across India was found to have a relatively narrow interquartile range with a few outliers at the top end. This was in large part due to the excellent solar resource available and low cost of solar PV installation. Despite there being no demonstrator plant able to validate these results, they are comparable, despit to other studies that have made similar technical and economic assumptions such as Eichhammer et al. (2019) [66], Armijo et al. (2020) [67], Palys et al. (2020) [68], Zhang et al. (2020) [69] and Fasihi et al. (2021) [70]. Figure 4 shows this and also the impact that the rate of LCOE reduction has on the LCOA: The median and minimum decreasing by 10.3% / 8.9% in the "optimistic" scenario and 18.7% / 17.2% in the "very optimistic" scenario (see Supplementary Material, Note 5 for further details). As the locations are ranked based on their "achievable" LCOA estimates, the "optimistic" and "very optimistic" curves are not smooth due to the highly non-linear nature of the problem and the model being able to re-design the plant, how its operated and even the ratio of wind and solar PV power sources used to minimise the LCOA. In general, the reduction in the LCOA is achieved by capitalising on the lower costs

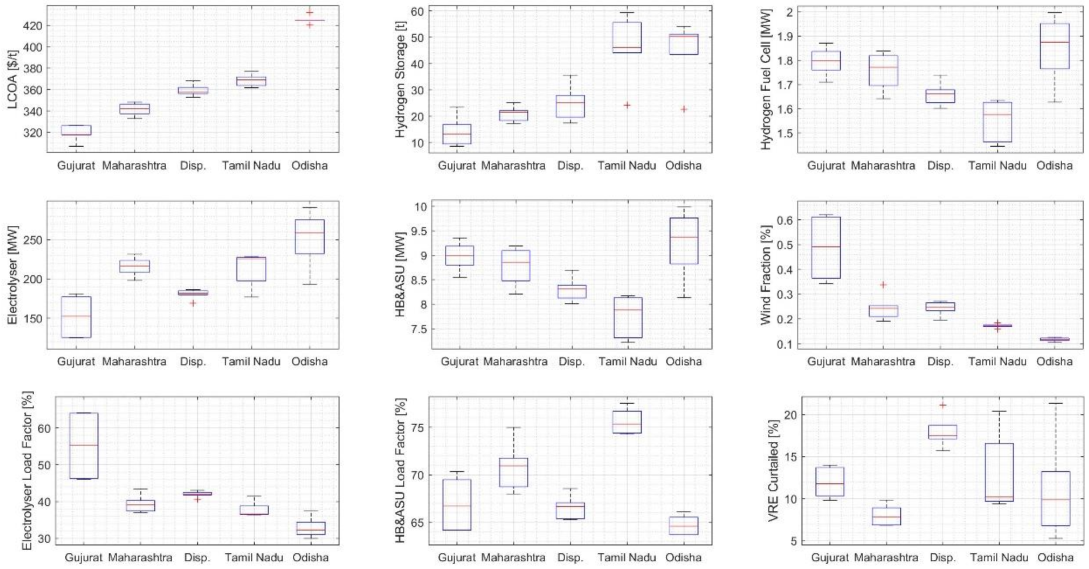

Figure 3: Boxplots for the five locations chosen of the objective function (LCOA), plant design and operation variables. HB/ASU is the ammonia synthesis process and the air separation unit. The underlying data and additional details can be found in Supplementary Material, Note 5.

attributable to the provision of plant flexibility required to manage the variable power supply.

For example, consider one of the locations in the lowest quartile, 22.0° north, 69.5° east which has and LCOA of 352, 329 and 286 USD/$t_{NH3}$ in the achievable, optimistic and very optimistic scenarios respectively (identifiable in Figure 4 as the location with the lowest optimistic result that deviates from the general trend). Its deviation in the optimistic scenario is because it notably increases the amount of wind used and changes its main method of flexibility from a hydrogen buffer to curtailment whereas most other locations merely reduced the flexibility method currently employed.

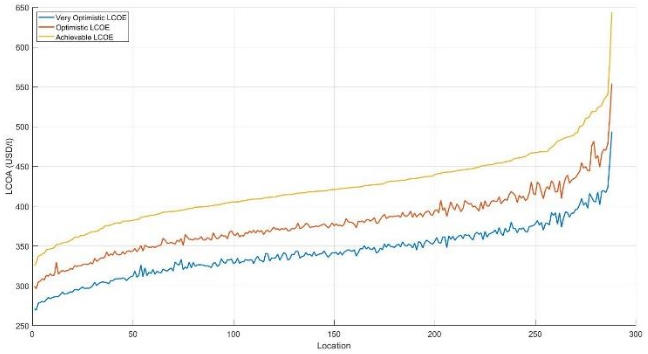

Figure 4: The LCOA for all 288 locations in each of the LCOE scenarios. all sorted by the "achievable" LCOA estimate by location.

From Figures 2 and 4 it is clear that the achievable LCOA varies significantly by state. Most notably that the west of the country has notably lower production costs than the east: the mean LCOA in the achievable scenario for the locations considered west and east of the meridian 80° east of Greenwich are 327 and 363 USD/$t_{NH3}$ (with standard deviation of 25 and 30 USD/$t_{NH3}$) respectively. The main reason for this is that there is better solar and wind resource in the west of the country [64] leading to 6.3% lower LCOE on average and enabling wind power, despite being still notably more expensive per unit energy compared with solar, to be competitive enough to form part of the VRE mix. This more dependable VRE power supply not only decreased the operational cost of electricity, but also enabled greater load factors in the electrolyser and synthesis units (7.7% and 11.1% on average respectively) and lower curtailment (by 11.7%).

Considering the results for the five locations selected, shown in Figure 3, enables further insights to be realised. For example, assessing the LCOA results it is clear that there is notable consistency across the six 5-year time periods considered from 1990-2019 and that the site in Odisha would have difficult business case when compared against other potential production estimates if it were not for the local demand and socio-economic factors. Assessing the design of the plants it can be seen that all are solar dominated (<25% wind) except for the location in Gujarat (which is due to the excellent wind resource) and have relatively similar sizing of the ammonia synthesis process and the air separation unit. However, looking at the electrolyser sizing, hydrogen storage and VRE curtailment, it is clear that how these plants differ in how they manage the inherent variability of these renewable energy sources: some favouring greater oversizing the electrolyser and larger hydrogen storage instead of / in addition to VRE curtailment. Unsurprisingly, the greater the flexibility required to manage this intermittency, the greater the cost and this is reflected in the electrolyser load factor and ultimately the LCOA.

As can be seen in Figure 5a, the best location by LCOA considered in India by [1] in 2019 at USD 636/$t_{NH3}$ is far from competitive with the current urea installations. However by 2030, this more spatially detailed analysis predicts that production at the best location (at 23.0° north, 69.5° east) can achieve an LCOA below USD 325/$t_{NH3}$ are competitive with the natural gas-based units, at 233 USD/tonne of urea on the basis of industrial cost of $CO_2$ at 50 USD/tonne [34]. However, it will be competitive with coal gasification, with the cost of production at Talcher at an projected 211 USD/tonne of urea produced[22], at 20 USD/tonne.

Figure 5a illustrates that the competitiveness of green urea is dependent on the cost of sourcing carbon dioxide. Accurate projections of when green urea will replace steam reforming or coal gasification techniques are then reliant on the cost variation of sourcing carbon dioxide.

There are already a number of sectors that require carbon dioxide as an input, such as fire extinguishers, carbonated beverages and refrigeration. There are various potential sources of carbon dioxide, most notably from power and industry[35] but in the long run this will have to be from biomass or direct air capture [36] if 'Net Zero' targets are to be met. The cost of carbon dioxide will largely be source-dependent [35] and with the absence of a large-scale carbon market it is hard to estimate what the equilibrium price will be.

Scenarios with a carbon tax have also been considered. In these cases, emitters will pay for the carbon to be disposed of. This means that the required $CO_2$ input will come at a negative cost. Green urea will be increasingly competitive in these scenarios, as the tax will push down the cost of green urea whilst also increasing the cost of hydrocarbon production pathways. Figure 5b illustrates that by 2030, green urea supported by a carbon tax of only 25 USD/t – much lower than many estimates of the social cost of carbon [37]– leads to green urea offering cost savings compared to natural-gas based production. It will also offer savings relative to coal gasification, with an LCOA under 360 USD/t of ammonia producing urea at a cost of 200 USD/tonne. The most promising location identified, in Gujurat, will be able to produce urea at 182 USD/tonne of urea. However, making comparisons at the state level it can be seen that the best location in Odisha requires such a tax (25 USD/t) to be competitive with the recently commissioned Talcher plant based on coal gasification.

Coal in India is currently subject to a tax (the 'Clean Environment Cess') at a cost of 400 Rs/ton. Translating this to a tax on the carbon emitted from the consumption of coal, this is equivalent to 3 – 6 USD/tonne of carbon dioxide produced from combusting the coal (depending on exchange rate fluctuations). In Figure 5c, this carbon tax is included, at 5 USD/tonne. Making the same comparisons that we did previously with Figure 5b, it can be seen that by 2030 green urea at the best national location is still offering significant savings compared to natural gas and coal-based production. However, the best green location in Odisha is now not competitive with the Talcher plant.

Significant price distortions exist in the market, particularly for Indian coal. Figure 6 quantifies the three most significant; under-pricing by Coal Industries Limited (CIL) - taken on the basis of the price premium e-auctions command over prices artificially set by CIL - [38] beneficial pricing for critical sectors such as power and fertilisers [39] and a preferential Goods and Service Tax (GST) rate compared to other minerals. These are listed in Supplementary Material, Note 3. By using the costings listed in [22] and detailed in Supplementary Material, Note 3, it was estimated that the cost of coal feedstock makes up approximately 68% of the total cost of production, showing a similar proportion to natural gas-based production [2]. Accounting for these price distortions would increase the input price of coal by nearly double.

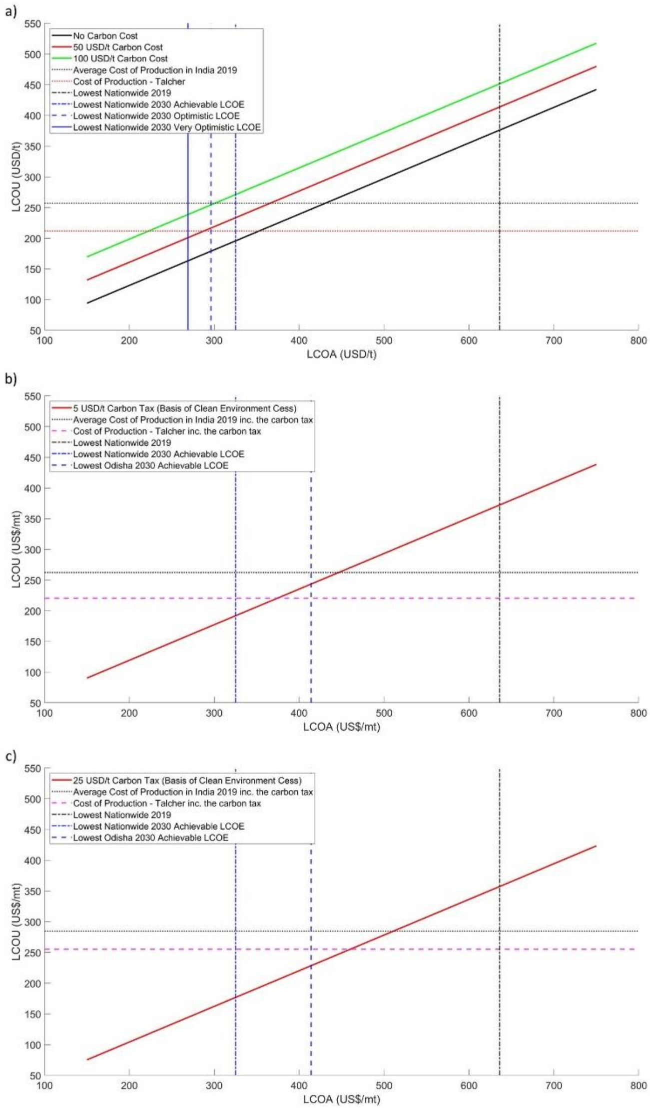

Figure 5: Benchmarking green ammonia production against conventional urea production (a) with their subsidies, (b) after the removal of coal distortions, and (c) after the removal of coal distortions and introduction of a carbon tax.

Figure 7 shows the impact of stripping out these price distortions from the cost of production from coal gasification at Talcher, at a cost of carbon dioxide of 20 USD/tonne, taken from [34]. Figure 7a shows that coal-based urea is still competitive in 2030 against green urea, but even by stripping out just the preferential prices this increases the costing to 240 USD/tonne. When the three major price distortions are stripped out, coal gasification is not competitive even against steam reforming by 2030, at a cost of 340 USD/tonne. Figure 7b includes the carbon tax of 5 USD/tonne implicit in the Clean Environment Cess on coal, putting green urea at even more of an advantage by 2030. In both figures it should again be noted that compared with green urea production within the state of Odisha the Talcher plant is still competitive even after removing one or two financial supports for coal depending on the cost of carbon dioxide.

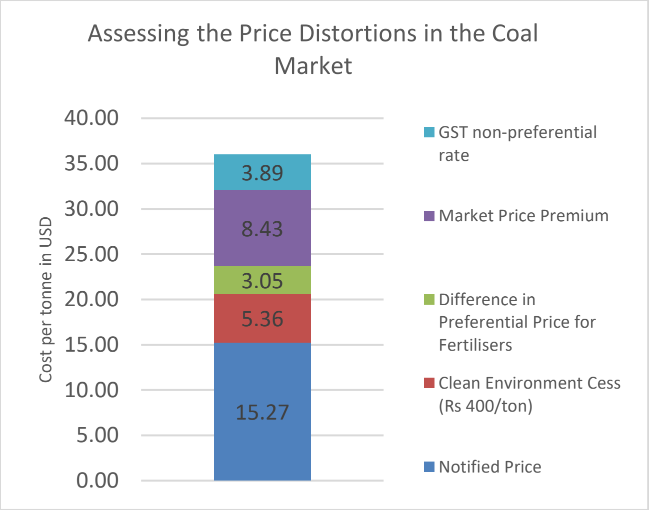

Figure 6: Quantifying the three major price distortions in the Indian coal market

The Indian natural gas market is also not subject to price discovery, with the price being worked out from the weighted average of four international benchmarks (See Supplementary Material, Note 3). In June 2020, the Indian Gas Exchange was launched, offering a platform for buyers and sellers to trade imported R-LNG via a double-blind bidding process. The average discovered price was 5.5 USD/MMBTU, over double the current notified price of 2.4 USD/MMBTU for domestic gas. This indicates that domestic gas is currently being under-priced, with producers indicating that the current notified price makes production unviable in many locations. This research examines the impact of 25%, 50%, 75% and 100% of the difference between the Indian Gas Exchange Limited (IGX) discovered price and the domestic notified price on the cost of production of urea from natural gas (see Supplementary Material, Note 3). These results are illustrated in Figure 7c and 7d, benchmarked against the cost of production from green urea.

As with the distortions in the Indian coal market, when these are stripped out green urea becomes increasingly competitive. A scenario where the domestic price under-priced by 50% of the current difference would put the average cost of production at 305 USD/tUrea, moving forward the year of cost parity with green urea to 2025 (see Table 2). Taking the under-pricing as the current difference between the IGX discovered price and the notified price would increase this to 353.7 USD/tonne, an increase of nearly 100 USD/tonne. This would see the year of cost parity be reduced to only a few years' time.

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| ***Benchmark*** | ***Year in which green urea is cost competitive ($CO_2$ at a cost of USD$20/ton)*** | ***Year in which green urea is cost competitive (carbon tax of USD$5/tonne)*** |
|---|---|---|
| Coal feedstock - Talcher | 2030 | 2029 |
| Coal feedstock - w/o preferential pricing | 2028 | 2027 |
| Coal feedstock- w/o preferential pricing or underpricing | 2024 | 2023 |
| Coal Gasification w/o preferential pricing, underpricing or preferential GST tax rate | 2022 | 2021 |
| Natural gas feedstock | 2028 | 2026 |
| Natural gas (25% Market Premium) | 2026 | 2025 |
| Natural gas (50%) | 2024 | 2023 |
| Natural gas (75%) | 2023 | 2022 |
| Natural gas (100%) | 2021 | 2020 |

Table 2: Benchmarking green ammonia production (achievable LCOE scenario) against conventional production methods to determine an estimate of the year of cost parity.

In India, urea plants often take more than a decade between project inception to commission. Talcher Fertilizer plant is a prime example; re-commissioning was announced in 2008, a consortium of was established in 2014 to revive it and it is estimated to be commissioned by 2023. The linear interpolation of the LCOA between 2019 and 2030 gives policy makers and industry an estimate of the date of cost parity.

Table 2 shows the year in which green urea will be competitive based on this linear interpolation. However, caution must be used when examining these dates, as they are based on a linear interpolation and the LCOA data is specific to New Delhi from [1]. Analysis with a consistent percentage drop of 6% per year – as costs will develop via a compound percentage decrease rather than linearly – shows that the linear interpolation is potentially conservative, underestimating the year of cost competition by almost a year in the midpoint of the range. Further analysis must be conducted for other locations in India.

## 5. Discussion

The results from this research are of important to both industry and policymakers as it provides key information about the future of the fertiliser sector. If the problems facing the sector are to be addressed, knowledge of the effectiveness of green urea as a solution is important. Green urea is shown to be cost-competitive with coal and natural gas-based methods of production in the near future in this research. The time until cost parity will be reduced if the pricing distortions to coal and natural gas are stripped out. This section identifies a policy roadblock to the uptake of green urea production, examines a possible solution and identifies the economic, social and environmental drivers for the government to adopt this solution and integrate green urea into the industry.

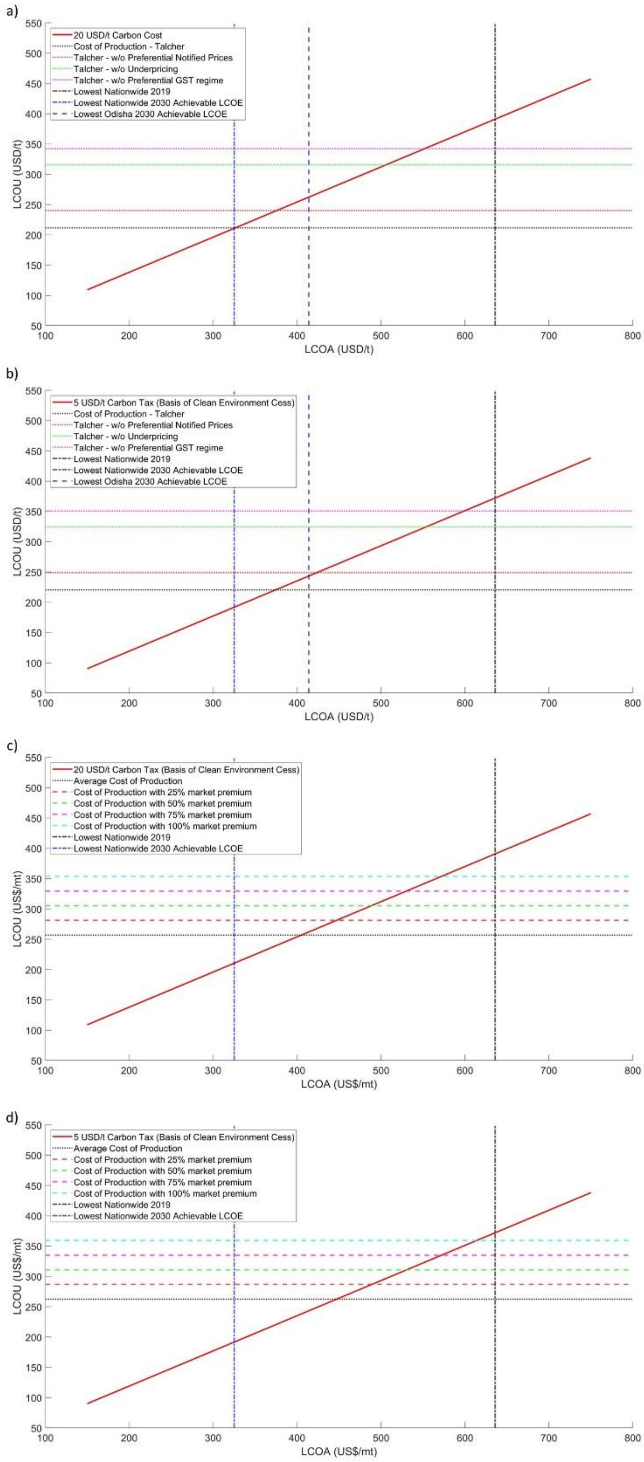

Figure 7: Comparing the levelized cost of green urea against the cost of production via coal gasification (a &b) and steam methane reforming (c & d) whilst stripping out price distortions under different carbon tax scenarios

However, a change in technology does not hold the answers to all the sector's problems. With nearly 50% of installations currently making a loss and significant subsidy payments in arrears [14], the current pricing regime from the government does not allow for the generation of significant funds to invest in large scale capital projects. The Centre for Science and the Environment's (CSE) Grain by Grain report examined the performance of the industry and recommended that to solve the problems facing the sector, decontrol was essential [33]. Industry has also been advocating for this for many years via the Fertiliser Association of India [40]. Freeing the sector from government control would introduce competition to the industry, bringing in space for innovations and reducing the subsidy bill of the government[33], which studies have shown to have one of the lowest margins of return of rural government spending[41].

Without a move towards a decontrolled industry, it is unlikely that green urea production will be adopted by the dates of cost parity this research estimates– especially because islanded green production will likely require a larger capital investment [42]. Government intervention in the sector stifles competition, with firms spending a miniscule amount on research and development [33] relative to chemical industries in other countries. Without competition, green urea being cost-competitive with hydrocarbon-based production pathways will not be as significant a driver to industry for its take-up, as firms will be unable to finance capital projects under the current pricing scheme[26].

It is important to remember that the industry is heavily controlled by the Government because of the essential role of fertilisers in India's economy. Subsidies are routed via industry to over 120 million farmers[43], ensuring sufficient supply at a fraction of global prices to the whole country and preventing a repeat of the periods of famine. As many sources note [16,33], while the fertilizer subsidy scheme has resulted in growth of agricultural productivity and increased food security, there are some negative effects, particularly with regard to the imbalanced/over-use of fertilizers and subsequent land degradation. Many stakeholders, including the Standing Committee on Chemicals and Fertilizers [16] have suggested examination of the current system to recommend changes that could be made.

NITI Aayog, the Indian Government's think tank, has constituted a committee to examine the feasibility of providing the fertilizer subsidy through Direct Benefit Transfer [16]. Instead of the subsidy being funnelled through industry, it would be transferred directly into farmers bank accounts after purchase at market price. This would open the industry up to competition, providing a route for green urea once it reaches cost parity. However, this system would also potentially benefit urea from installations such as Talcher. Coal gasification would provide a cheaper alternative to the current natural gas-based production [22] but would be more environmentally damaging than green urea. Ammonia produced via coal has over double the carbon dioxide intensity of steam reforming[23] and widespread use of this technology instead of green production methods would create additional challenges for India to achieve its Nationally Determined Contributions (NDCs) for emissions reductions and ultimately carbon neutrality[25]. With the current distortions in the Indian coal market, coal gasification would be slightly more cost-competitive than green urea and would be favoured by this policy. The removal of just one – beneficial pricing to 'essential' sectors such as fertilisers – would bring green urea in several locations back to cost parity.

There are significant drivers for the Government of India to incentivise a shift to green urea and ammonia production, beyond the common drivers also offered by the coal gasification route. These can be broadly split up into three categories, as defined in [44] as the characteristic aspects of sustainable development; Social, Economic and Environmental.

Many studies have recognised that renewable energy provides more jobs than an equivalent fossil fuel-based power source[45]. CEEW, a New Delhi based think-tank, estimates that a transition to green ammonia production could help create 200,000 jobs by 2050 along the hydrogen supply chain, compared to the 20,000 currently involved in the domestic natural gas supply chain. A brief estimate of the jobs created from a green ammonia plant in New Delhi, based on the rated size of the components of the green urea/ammonia plant from[1] and job intensity figures from [46] adjusted for India according to [47] estimates that 5,158 full time equivalent (FTE) job-years could be created as a result of that installation. Direct employment ratios for the solar and wind components of the islanded plant were taken from [48].

One of the most significant drivers behind the revival of the five mothballed installations was the 'Make in India' campaign, aiming to promote self-sufficiency in the fertiliser industry and close the current demand gap of 25% in 2018-2019 [16]. Green urea production would take this one step further, reducing dependency on imported re-liquefied natural gas (R-LNG) as a feedstock and fitting with the 'Make in India' campaign without resorting to the environmentally damaging coal gasification route. This would reduce the outflow of foreign capital, improving the balance of payments and reducing the impact that fluctuations in the global oil and gas markets has on the cost of production and the government's subsidy bill. India is one of the locations identified in [1] as showing promising potential for islanded green ammonia production due to its excellent renewable energy resources. Investing in green urea and ammonia production could lead to it becoming a net exporter of nitrogenous fertilisers rather than the global second largest importer of ammonia[2] and the largest of urea[49]. However, the variation in the achievable LCOA by state and specifically the west/east differences previously identified (Figure 2) need to be taken into account when incentivising the uptake of this technology. There will likely still be a requirement to ensure that production is spread across the country for security of supply and in order to meet the notable demand that exists in east India. Despite Uttar Pradesh, Madhya Pradesh, Punjab, Haryana and Rajasthan being dominant states for agriculture, there is still notable demand for urea in other more eastern states such as West Bengal, Bihar and Odisha [65] A key question is whether in those states, particularly to the east of the country, where the LCOA of local green production is higher the most cost effective solution in the future would be to rely on domestic interstate trade or international imports instead. This forms part of our future work due to the notable requirement for the predicted future prices of green, blue and brown ammonia and/or urea in order to make accurate predictions of future competitiveness.

Islanded green urea production offers significant environmental benefits compared to coal gasification or natural gas-based production. Studies have identified India as one of the countries most at risk from climate change [50] and ammonia production is the third largest emitter of greenhouse gas emissions from the manufacturing sector, after steel and cement[8]. Islanded urea production fuelled by solar and wind would offer an avenue to decarbonise the sector. It would also significantly reduce other pollutants such as sulphur dioxides, fine particulate matter and nitrous oxides. Based on LCA data for the hydrogen production from [51] and social costing of pollutants from [48] and [52] coal gasification would require an extra \$630/t$NH_3$ produced and steam reforming an estimated \$200/t$NH_3$ produced to account for the harm to human life in India. The vast majority of this quantified external cost is due to the $CO_2$ emissions.

## 6. Conclusion

This research has shown that islanded green urea production holds promising potential as a future source of nitrogenous fertilisers for India. The industry faces significant challenges, from aging capacity to financial pressures caused by government intervention and significant environmental externalities associated with production. Due to India's significant renewable energy resources, green urea production is a strong option to solve these problems and will be competitive with natural gas means of production by 2030, at 212 USD/tUrea in the best location (assuming USD 20/t $CO_2$). Competitive with coal gasification, taken as 211 USD/tUrea produced in Talcher [22], even before financial support for fossil-fuel based production is removed or re-allocated.

It has also identified the two major policy roadblocks to uptake of islanded green urea production, namely the current subsidy and pricing regime in the urea industry and the price distortions in the Indian coal and natural gas market. Stripping out price distortions in the Indian coal market, even just the preferential rates offered to power and fertilizer companies by Coal Industries Limited (CIL)[39], will bring green urea to cost parity before 2030. Additionally, if the IGX discovered price is taken as the price Indian produced natural gas should be, this would put green urea as competitive within the next few years. However, this research only examined the relative levelized cost of green urea and this has its limitations, particularly in its applications for industry. A cashflow analysis of green urea would be a valuable next step to assess the viability of islanded production in India, particularly due to the high capital expenditure of green ammonia production[42] and cost of working capital in the industry[57] It is important to note however, that coal gasification also has high upfront capital requirements relative to natural gas [42], with the Talcher installation costing almost double the capital expenditure than the other four revived plants. Moreover, while the water feedstock required for green production was costed in this study, it must be noted that notable portions of India are water stressed while others have significant seasonal flooding. These challenges are only likely to be exacerbated with greater global warming. The provision of the water feedstock thereby requires further consideration when conducting a more detailed plant design for any of these locations. Desalination, where appropriate, may likely be essential for some locations and through its implementation may serve a dual purpose to relieve some of this water stress as that process could be affordably oversized due to it being a small proportion of the total cost of urea production.

This paper has highlighted the viability of green urea production to substitute conventional fossil-fuel based production and how quickly this substitution could take place if government supports are removed or re-allocated. Given the importance and magnitude of nitrogenous fertiliser demand and that high-emitting coal gasification has been revisited as a method of production, India is a prime example of where financial support to transition to green production would have a substantial return on investment: achieving many sustainable development goals (SDGs), providing substantial high quality jobs and cultivating an industry that has substantial potential for growth due to green ammonia's predicted use in power sector and international shipping. If a 2.19Mt p.a. capacity (comparable to ammonia plants currently being commissioned, Supplementary Material, Note 3) production plant was constructed at each of the five locations considered (52.2% of India's 2019 capacity [59]) this would mitigate 3.28-5.17kg $CO_2$ equivalent per kg of urea (depending on the unused hydrocarbon feedstock) or 35.9-56.6Mt $CO_2$ equivalent per year. These alone would therefore mitigate between 21.7±2.7% and 34.3±4.3% of India's emissions and therein between 2.6±0.3% and 4.1±0.5% of global emissions from the manufacture of synthetic nitrogen for fertilisers [60]. These and additional emission mitigation through the construction of further green urea plants to replace old existing plants would enable / complement the production of green ammonia for shipping fuel. The World Bank's 2050 shipping scenarios assumed a demand for green ammonia produced in India between 95 and 248Mt per year (10-27% of 2050 global demand). This corresponds to between 27-70% of 2016 energy demand for shipping fuel [61] or 183-475Mt $CO_2$ equivalent per year [62]. Capitalising upon the benefits that can be gained through the production of green ammonia production in India would accelerate India and the world's pursuit of carbon neutrality.

While there are financial, corporate and political barriers to overcome one should take encouragement from a poignant comment made at OXGATE/CEEW's "India's Green Ammonia Opportunity" Workshop that while it is widely accepted that subsidy or incentives are required if green ammonia is to compete with brown ammonia in the short-term, India already has the world's largest support for ammonia production and the some of the lowest prices for installed solar PV. What is required is that this state support is directed towards green production instead to achieve Net-Zero emissions in this significant sector.

Future research should also consider the effect of economies of scale. Conventional production of ammonia and subsequently urea is typically from large, capital intense facilities built to achieve economies of scale[58]. This research assumes a linear relationship between output and cost, with no economy of scale. In reality there will initially be difficulties in scaling up electrolytic production to similar magnitudes of conventional production, as only small-scale green ammonia plants currently exist. Solving the problems of scaling up production will be important if islanded green urea production is to compete with coal gasification as the replacement technology for the Indian urea industry. This paper provides a brief overview of the industry and the conditions required for the uptake of green ammonia for the fertiliser sector. The creation of a roadmap for green urea in India, following from the example of Japan's hydrogen economy roadmap, should be formulated and will greatly help with the transition to a decarbonised fertiliser industry. To achieve this, future research will build upon the LCOA map (Figure 2) and more detailed analysis to conduct a systematic country-wide optimisation to locate new capacity. This will take into account the costs of transportation, synergies due to existing infrastructure, age and status (i.e. if retrofitting has been conducted to extend lifetime) of the plants, and the international import alternatives.

## Conflicts of interest

There are no conflicts to declare.

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## Notes and references

1 R. Nayak-Luke, R. Bañares-Alcántara, Energy & Environmental Science, 2020,13, 2957-2966
2 Yara, Yara Fertilizer Industry Handbook, 2018
3 J. W. Erisman, M. A. Sutton, J. Galloway, Z. Klimont and W. Winiwarter, Nature Geoscience, 2008, 1, 636-639
4 Philibert, C. Producing ammonia and fertilizers: new opportunities from Renewables, IEA, 2017
5 O. Siddiqui, I. Dincer, Energy Conversion and Management, 2019, 195, 866-884
6 N. Ash, T. Scarborough, Sailing on Solar: Could green ammonia decarbonise international shipping, 2019
7 R. Carlo, B. J Marc, S. F. Santiago, T. Smith, K. Søgaard, Aggregate Investment for the decarbonisation of international shipping, 2020
8 CEEW, Sustainable Manufacturing for India's Low-Carbon Transition, 2019
9 S. Chander, Climate Change and Indian Agriculture, Indian Journal of Fertilizers, 2018
10 United Nations, World Population Prospects 2019

11 Government of India, Annual Report 2017-2018, Indian Department of Fertilizers, 2018
12 International Labour Organization, ILOSTAT database, 2020 https://ilostat.ilo.org/
13 International Fertilizer Association, IFASTAT database, (accessed 29th June 2021) https://www.ifastat.org/databases
14 Fertiliser Association of India, Annual Report 2018-2019, 2019
15 Fertiliser Association of India, Annual Report 2015-2016, 2016
16 Government of India, Ministry of Chemicals and Fertilizers, Study of Fertilizer Subsidy System, 2020
17 Ministry of Agriculture, Cooperation and Farmers Welfare, Agricultural Statistics at a Glance 2018, 2018
18 Fertiliser Association of India, Performance Improvement in Ammonia Plants in India, 2013 LINK
19 Ministry of Petroleum and Natural Gas, https://petroleum.nic.in
20 PDIL, Pre-Feasibility Report for Gorakhpur Unit, 2016
21 Department of Fertilizers, Sanglur-Indian Fertilizer Scenario, 2018
22 PDIL, Pre-Feasibility Study for Talcher Fertilizers Limited, 2017
23 Institute for Industrial Productivity, Industrial Efficiency Database http://www.iipinetwork.org/wpcontent/Ietd/content/ammonia.html
24 IEA, India 2020: Energy Policy Review, 2020
25 Climate Action Tracker, Climate Action Tracker India, 2019
26 S. Chander, Urea Industry is in Crisis, Indian Journal of Fertilizers, 2018
27 A. Chakraborty, Explosion damages Namrup-II Unit, Indian Telegraph, 2020
28 R. Nayak-Luke, R. Bañares-Alcántara and I. Wilkinson, Industrial & Engineering Chemistry Research, 2018, 57, 14607-14616
29 Copernicus, ERA5 Database, 2019 https://cds.climate.copernicus.eu/cdsapp#!/home
30 J.G Driver, R. E. Owen, T. Makanyire, J. A. Lake, J. McGregor, P. Styring, Frontiers of Energy Research, 2019, 7, 88
31 Paradeep Phosphates Limited, Pre-Feasibility Report for Expansion, 2017
32 I. Dincer, Y. Bicer, International Journal of Hydrogen Energy, 2017, 42, 33.
33 Centre for Society and the Environment, Grain by Grain: A rating of the Fertilizer sector, 2019
34 Z. Cesaro, R. Nayak-Luke, R Bañares-Alcántara, Energy Storage Techniques: Power-to-X, 2020
35 IPCC, Sources of $CO_2$, 2005
36 IEA, Putting $CO_2$ to use, 2019
37 N. Stern, The Stern Review, 2006
38 Coal India Limited, Annual Report 2018-2019, 2019
39 Coal India Limited, Price Notification dated 08/01/2018, 2018
40 S. Chander, Unlocking Potential of Fertilizer Sector, Indian Journal of Fertilizers, 2015
41 S. Fan, A, Gulati, S. Thorat, Investment, Subsidies and Pro-Poor Growth in Rural India, 2007
42 Trevor Brown, Ammonia Plant Cost Comparisons, Ammonia Industry, 2017
43 Office of the Registrar General & Census Commissioner India, 2011 Census Database, 2011
44 G. H. Brundtland, Our Common Future, 1987
45 D. Gioutsos, A. Ochs, The Employment Effects of Renewable Energy Development Assistance
46 Council of Economic Advisers, Estimates of Job Creation from the American Recovery and Reinvestment Act of 2009, 2009
47 J. Rutovitz, S. Harris, Calculating Global Energy Sector Jobs: 2012 Methodology, 2012
48 CEEW, Greening India’s Workforce, 2017
49 Argus Media, Urea trade volumes slip in 2018, 2019
50 K. Ricke, L. Drouet, K. Caldeira, M. Tavoni, Nature Climate Change, 2018, 8, 895-800
51 A. Mehmeti, A. Angelis-Dimakis, G. Arampatzis, S. J. McPhail, S. Ulgiati, Environments, 2018, 5(2), 24
52 I. Parry, D. Heine, E. Lis, S, Li, Getting Energy Prices Right: From Principle to Practice, 2014
53 World Bank, India-Nangal Fertiliser Expansion Project, Report No. 3760, 1981
54 R. E. J. Culpepper, Import Substitution, Self-Reliance and the Choice of Techniques: A Study of the Indian Fertilizer Industry, 1975
55 M. Alfian, W. W. Purwanto, Energy Science and Engineering, 2019, 7, 292-304
56 F. Barzagli, F. Mani, M. Peruzinni, Green Chem. 2011, 13, 1267-1274
57 S. Chander, Performance of Fertilizer Sector during 2017-2018, Indian Journal of Fertilizers, 2019
58 C. Malins, What role for electromethane and electroammonia in European Transport’s low carbon future, 2018
59 Ministry of Chemicals and Fertilizers, Study of System of Fertilizer Subsidy, M.o.C.a. Fertilizers, Editor. 2020: New Delhi.
60 S. Menegat, A. Ledo, R. Tirado, Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture, Scientific Reports (Preprint) https://doi.org/10.21203/rs.3.rs-1007419/v1
61 Englert, D., Losos, A., Raucci, C., Smith, T., 2021. The Potential of Zero-Carbon Bunker Fuels in Developing Countries. World Bank, Washington, DC. World Bank. https://openknowledge.worldbank.org/handle/10986/35435
62 J. Tattini, S. McBain, International Shipping, IEA Report November 2021, https://www.iea.org/reports/international-shipping [Accessed 22nd March 2022]
63 N.D. Pawar, H.U. Heinrichs, C. Winkler, P.M. Heuser, S.D. Ryberg, M. Robinius, D. Stolten. International Journal of Hydrogen Energy, 2021, vol 46, 54, 27247-27267.
64 India’s Photovoltaic Power Potential Map obtained from the “Global Solar Atlas 2.0” Solargis s.r.o. on behalf of the World Bank Group, *https://globalsolaratlas.info/download/india* [Accessed 22nd March 2022]
65 2015-16 Agriculture Census, Department of Agriculture & Farmers Welfare, Government of India, https://agcensus.dacnet.nic.in/DatabaseHome.aspx [Accessed 22nd March 2022]
66 W. Eichhammer, et al., *Study on the Opportunities of "Power-to-X" in Morocco: 10 Hypotheses for Discussion*. 2019, Fraunhofer ISI
67 J. Armijo, and C. Philibert,. International Journal of Hydrogen Energy, 2020. **45**(3): p. 1541-1558
68 M.J. Palys, and P. Daoutidis, Computers & Chemical Engineering, 2020: p. 106785.
69 H. Zhang, et al. Applied Energy, 2020. **259**: p. 114135.
70 M. Fasihi, et al,. Applied Energy, 2021. 294: p. 116170.