Harvesting Sustainability: Cost-competitiveness of Green Fertilizer Value Chains in Western Africa

Marco Schamel
Institute for Energy Networks and Energy Storage (FENES)
University of Applied Sciences (OTH) Regensburg
Regensburg, Germany
marco.schamel@oth-regensburg.de

Anton Achhammer
Institute for Energy Networks and Energy Storage (FENES)
University of Applied Sciences (OTH) Regensburg
Regensburg, Germany
anton.achhammer@oth-regensburg.de

Leon Schumm
Institute for Energy Networks and Energy Storage (FENES)
University of Applied Sciences (OTH) Regensburg
Regensburg, Germany
leon1.schumm@oth-regensburg.de

Michael Sterner
Institute for Energy Networks and Energy Storage (FENES)
University of Applied Sciences (OTH) Regensburg
Regensburg, Germany
michael.sterner@oth-regensburg.de

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***Abstract*—The use of nitrogen fertilizers in Sub-Saharan Africa is low compared to other regions of the world, leading to inadequate crop yields. Furthermore, conventional production from fossil fuel-based ammonia is highly emissions-intensive, making decarbonization urgent. Local production using green hydrogen, sourced solely from solar energy, water, and air, could address both agricultural and climate challenges. This study focuses on Ghana, where nitrogen inputs are among the lowest globally. Using an open-source framework, we evaluate high-resolution production costs for sustainable ammonia and examine two decarbonized pathways: aqueous ammonia and urea. It is found that cost estimates with current assumptions mostly exceed historical prices. However, given their resilience to global market disruptions and expected future cost decreases of the technologies used, these sustainable approaches represent a promising pathway for development in Sub-Saharan Africa.**

***Index Terms*—Fertilizer production, Food security, Green ammonia, Green hydrogen, Western Africa**

I. Introduction

The manufacturing of inorganic nitrogenous fertilizers is a major prerequisite of modern agriculture worldwide. Made possible by the synthetic production of ammonia in the Haber-Bosch process, invented by Fritz Haber and Carl Bosch in the beginning of the 20th century, the synthetic provision of the nutrient nitrogen to plants allowed for unprecedented levels of nutrient input [1]. This drastically enhanced agricultural productivity in the following decades [2]. By now, food provision for half of the world's population is only possible owing to precisely this process [1]. This development has its caveats however: The production of ammonia uses significant amounts of fossil fuels, accounting for 1.2 % of global energy-related CO_2 emissions [3]. Additionally, not all world regions are able to profit from it equally. Whilst fertilizer application rates in many countries vastly increased over the last century, especially countries in Sub-Saharan Africa do not have sufficient access to fertilizers, hampering land productivity and human development [4]. Hence, the current system of nitrogenous fertilizer production and distribution can be regarded as both harmful to the environment and unjust for large parts of the world's population. Considering global ambitions to reduce greenhouse gas emissions to zero by the middle of the century [5] as well as the sustainable development goal to eradicate hunger globally [6], a paradigm shift in fertilizer procurement is necessary. This paper investigates a promising approach aimed at combating both the negative climate impacts and the unjust dispersion of fertilizers. Using green ammonia produced from renewable electricity, regions in the Global South can be enabled to locally procure decarbonized nitrogenous fertilizer products [7]. As the Western African country Ghana both has one of the lowest nitrogen fertilizer application rates globally [8] and does not host a domestic fertilizer production facility [9], it is chosen as a case study to evaluate the cost-competitiveness of decarbonized fertilizer supply chains with the help of a techno-economic model. In detail, both the direct use of diluted ammonia as a nitrogenous fertilizer as well as the conversion into the commonly used fertilizer product urea are investigated. By drawing on current and future cost assumptions as well as historical price data, costs for green fertilizers are compared with local prices for conventional products. By doing so, light is shed on the feasibility and prospects of net-zero domestic production of nitrogenous fertilizer in Western Africa.

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II. Relevance and Production of Nitrogenous Fertilizers

Mineral fertilizers enable around half of global food production by supplying essential nutrients - potash, phosphate, and nitrogen - that boost crop yields [1]. Among these, nitrogen-based fertilizers are the most energy-intensive to produce, requiring about 19.3 $kWh/kg_{Product}$, compared to 1.8–2.1 $kWh/kg_{Product}$ for phosphate- and potash-based types

[10]. This is due to the energy demands of ammonia synthesis, which accounts for 90% of the fertilizer sector's emissions and 2% of global energy use [11]. Decarbonizing ammonia production is therefore central to decarbonizing the fertilizer industry. Global application of nitrogenous fertilizers reached 109 Mt of nitrogen in 2020 [12]. Use of nitrogen fertilizers varies significantly by region. Sub-Saharan Africa applies just 22 kg of nitrogen per hectare of cropland - among the lowest globally - compared to over 190 kg/ha in countries like China and Saudi Arabia [8]. This disparity in fertilizer application is mirrored in agricultural output. Countries with higher nitrogen inputs tend to achieve significantly higher cereal yields [13]. This in turn has negative consequences on countries with low fertilizer application rates, causing sub-par agricultural output levels and increased food insecurity [14].

Ammonia is the key precursor for all nitrogenous fertilizers, produced almost exclusively via the Haber-Bosch process [15]. This involves synthesizing ammonia (NH_3) from hydrogen and nitrogen under high temperature (400-650 °C) and pressure (100–400 bar) using an iron catalyst according to Equation (1) [16] [3].

$$\mathrm{N_2 + 3\,H_2 \rightleftharpoons 2\,NH_3} \tag{1}$$

Most hydrogen is currently sourced from natural gas via steam methane reforming (SMR), a process responsible for substantial CO_2 emissions [3]. Global average emissions are estimated at 2.4 t CO_2 per tonne of ammonia [17]. Nitrogen is typically obtained through cryogenic air separation [18]. For a sustainable ammonia production pathway, the fossil-based hydrogen is replaced with green hydrogen from electrolysis powered by renewable electricity [19]. Ammonia is commonly processed further into urea ($CO(NH_2)_2$), a widely used solid fertilizer. This involves reacting ammonia with CO_2 to form ammonium carbamate, which is then dehydrated to urea (Equation (2)) under high pressure (145 bar) and temperature (180 °C) [20], [21].

$$\mathrm{2\,NH_3 + CO_2 \rightleftharpoons CO(NH_2)_2 + H_2O} \tag{2}$$

To fully decarbonize not only ammonia, but also urea production, CO_2 must be sourced sustainably, e.g., via Direct Air Capture (DAC), which uses chemical sorbents to extract CO_2 from ambient air [22].

III. Methods

This chapter gives insights on the methodology utilized to calculate production costs both for green ammonia and the subsequent conversion into sustainable urea. After introducing the considered scenarios, details on the methodological framework and data sources are provided.

A. Scenario design

Two scenarios are compared with each other: direct ammonia usage and the conversion of ammonia to urea. Figure 1 gives an overview of the considered scenario pathways.

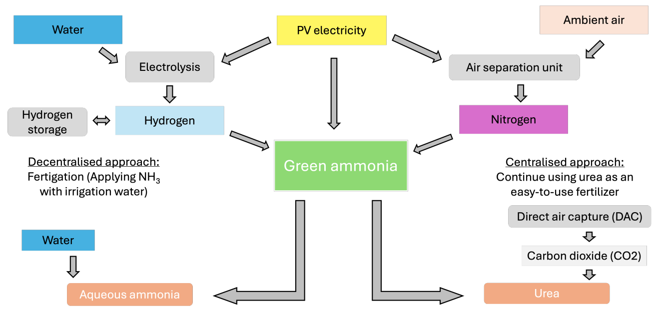

Fig. 1. Overview of considered fertilizer supply scenarios

Currently, about 80% of the global ammonia supply is converted to different fertilizer products, making ammonia an invaluable precursor to all nitrogenous fertilizers [23]. It is also possible to make use of ammonia in diluted form, so-called aqueous ammonia. The ammonia solution is made available to the plants by getting injected into an existing irrigation system in a process called fertigation [24] [25]. This approach removes the need for a further processing unit and allows for decentralized green ammonia utilization. The main challenge for the African context however is the need for an irrigation system. Currently, a mere 6% of African croplands are equipped with irrigation systems [26]. It is shown however that especially an increase in distributed irrigation is advantageous for smallholder farmers in order to increase crop yields and fight undernourishment [27].

B. The open-source modeling framework model.energy

The calculation of fertilizer production costs is based on modeling results generated by the open-source framework *model.energy/products* which facilitates cost calculation for the production and transport of various hydrogen-based energy carriers for nearly all locations worldwide [28]. To this end, time series data for electricity generation from wind energy and solar PV is derived by the Python package *atlite* [29]. This code package produces spatially-resolved technology-specific electricity production time series drawing on weather data from the ERA5 global reanalysis dataset published by the European Centre for Medium-Range Weather Forecasts (ECMWF) [30]. Based on the time-varying electricity production and certain technology and cost assumptions, *model.energy/products* calculates projected production costs for the years 2020, 2030, 2040, and 2050 utilising the open-source framework PyPSA (Python for Power System Analysis) [31]. In the following, a brief overview over the system design of the ammonia synthesis plant modeled by *model.energy/products* is given.

C. Calculation of green ammonia costs

For the sustainable production of ammonia, several production modules are needed: hydrogen electrolysis, an air separation unit, and the ammonia synthesis reactor. The different components are connected by fixed efficiencies depending on the selected year of installation. For electricity generation, only solar PV is utilised, enabling a location-independent installation of the ammonia plant. A location in the North-East region of Ghana is selected due to the higher solar irradiance in Ghana's North compared to the Southern part of the country [32]. The simulation is performed in a resolution of three hour timesteps with weather data from 2011. Whilst the hydrogen electrolysis is modeled to be able to follow the time-varying solar PV generation instantly, the Haber-Bosch synthesis plant is assumed to have a minimum load of 30%, owing to the dynamics of the chemical process [33]. The produced ammonia is temporarily stored in a storage system in order to guarantee a constant output. Furthermore, pressurized hydrogen tanks balance out mismatches in hydrogen supply and demand, whilst battery storage is deployed to ensure sufficient electricity supply for electrolysis and ammonia synthesis. The resulting Levelized Costs of Ammonia (LCOA) are calculated for different values of the Weighted Average Cost of Capital (WACC). Generally, the cost of capital depends both on technology- and country-specific risks [34]. For instance, IRENA's evaluation of electricity production costs assumes values of 7% and 10%, reflecting standard capital costs for utilities and those applicable for higher-risk environments, respectively [35]. To gain insights into the WACC's importance, ammonia costs are calculated for discount rates of 5%, 10%, 15%, 20%, and 25%.

D. Approximation of urea synthesis costs

To facilitate the conversion form ammonia to urea, an urea synthesis reactor is needed, taking ammonia and carbon dioxide as input. For the sake of simplicity, power consumption of the synthesis unit is neglected in the calculation. Therefore, only capital and operating costs of the synthesis reactor as well as expenditures for CO_2 provision are considered.

Since the produced urea is supposed to be climate neutral, CO_2 is sourced from ambient air using DAC. *Model.energy/products* provides the user with an option to model carbon dioxide provision as part of carbonaceous energy carrier production (e.g. methanol). The framework is utilised to model provision costs for the amount of CO_2 needed to synthesize the urea. Considering the stoichiometry of the conversion, for each kg of urea, 0.74 kg of CO_2 is needed.

Data on the urea synthesis reactor itself mainly stems from [21], where the whole process chain of green urea production powered by hydroelectricity and utilizing CO_2 from cement flue gas is investigated.

IV. RESULTS

In the following, cost results for sustainable fertilizer production in Ghana are presented. Firstly, the sole production of ammonia is considered, directly drawing on modeling results generated by *model.energy/products*. Secondly, taking the ammonia production costs as a basis, costs for a further conversion to urea are approximated drawing on *model.energy/products* for CO_2 provision and data from [21] for urea synthesis costs.

A. Green ammonia production costs in Ghana

To investigate the effect of decreasing technology costs in future years, ammonia production costs are firstly calculated for the years 2020, 2030, 2040, and 2050. Results are shown in Figure 2.

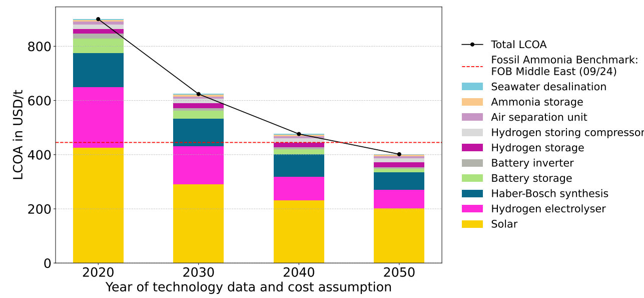

Fig. 2. Levelized costs of ammonia production in Ghana, varying assumed year of installation

The main cost components are electricity generation by solar power and hydrogen electrolysis, accounting for 47% and 25% of total ammonia costs in 2020, respectively. Due to expected cost reductions, the cost share of electrolysis decreases to 17% by 2050, contributing just slightly more than the Haber-Bosch synthesis (16%), whose cost reduction is not as as pronounced compared to the electrolysis. Comparing the cost results with a current production benchmark for green ammonia [36] shows that current production costs for green ammonia are about twice as high compared to its fossil counterpart. However, when taking into account the projected cost reductions for the plant's equipment (especially PV plant, electrolyser, and ammonia synthesis), production costs could be in the vicinity of current fossil prices between 2040 and 2050 – without any subsidies.

The production costs depend highly on the assumed WACC which is used as an indicator for the overall interest rate that applies to the project's investment costs [37]. Investors expect higher return rates for investments in countries with higher perceived investment risks (e.g. due to little developed financial markets or political instability), leading to an increased WACC. Furthermore, investments in novel technologies like green hydrogen or green ammonia, are considered riskier due to the lack of an established market and commercial implementation [38] [39]. Therefore, the applied interest rate is varied in the *model.energy/products* interface to quantify the WACC's influence on production costs. Starting from a base value of 5%, the effect of an increased rate to up to 25% for the base year of 2020 is shown in Figure 3.

A strong near-linear correlation between the WACC and the corresponding LCOA is evident. Especially when considering higher values of 15% or 20% (not uncommon for countries in Sub-Saharan Africa [40]), cost-competitiveness with fossil production gets further out of sight. This underscores the importance of financial support mechanisms aimed at lowering the perceived investment risk and the WACC.

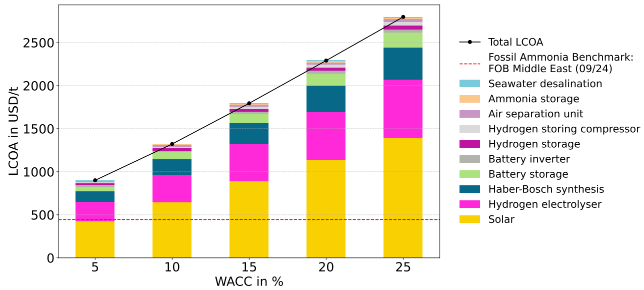

Fig. 3. Levelized costs of ammonia production in Ghana for 2020, varying the WACC

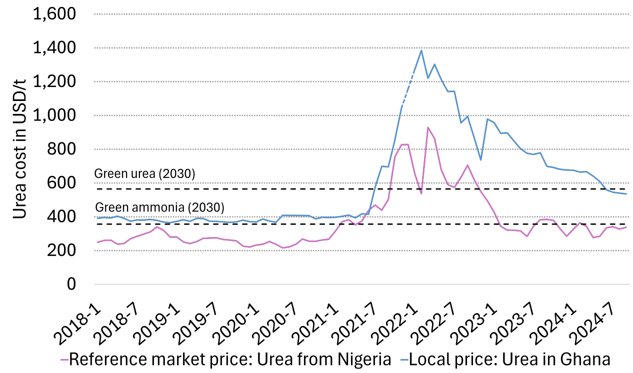

Fig. 4. Comparison of modeled green ammonia and urea production costs with historical urea prices in Ghana

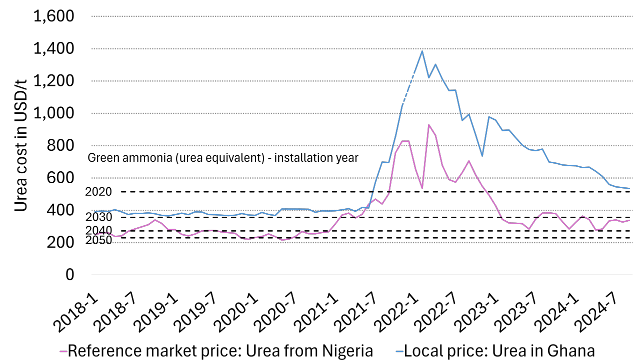

Fig. 5. Comparison of modeled green ammonia costs for different years with historical urea prices in Ghana

B. Green urea production costs in Ghana

Taking an optimistic approach with an interest rate of 5% for ammonia production and 10% for urea synthesis, green urea production costs are composed as follows: For each tonne of urea, 514.4 USD (71%) are attributed to ammonia production, while CO_2 provision and the urea synthesis reactor account for 158.2 USD (22%) and 49.8 USD (7%), respectively. This results in levelized costs of 722.5 USD per tonne of urea.

C. Cost-competitiveness of green ammonia and urea in Ghana

The obtained cost results are set into context by comparing them to historical price data for conventional urea supply in Ghana. Whereas the benchmark in Figure 2 and Figure 3 is referring to the mere production cost of conventional ammonia, this chapter shows actual fertilizer prices, both international and domestic, which will be compared with the obtained cost projections for decarbonized production. The approach is twofold - as explained in Section III-A, both direct usage of aqueous ammonia and conversion to urea are compared. To make the scenarios comparable, costs for ammonia production are scaled to costs for producing an amount of urea with the equivalent nitrogen content. The results are shown in Figure 4.

It gets apparent that although cost estimates for the sustainable ammonia and urea routes exceed the historic urea prices, cost-competitiveness is given during the price surges in late 2021 to mid-2022. This reveals a major advantage of the decarbonized concept: Since the main feedstocks are simply solar irradiation and ambient air, there is no dependency on volatile price developments in global markets during the production lifetime of the plant, leading to a price-stable supply with fertilizers.

The chosen year of technology assumption is highly influential on the overall production cost. To illustrate this, Figure 5 shows the development of projected ammonia production costs for different years in comparison to historical prices. It is evident that the cost reduction in 2030 alone leads to production costs for aqueous ammonia constantly below local domestic fertilizer prices in Ghana, showcasing the potential for this sustainable production approach. When considering assumptions for 2040 and 2050, costs for aqueous urea even reach historical reference market prices for conventional urea from Nigeria.

V. Discussion

The obtained results are now discussed by comparing the findings to various literature values and elaborating on methodological limitations.

A. Comparison with literature cost estimates

A wide range of projected green ammonia costs can be found in literature, depending on system design, considered location, and technology data assumptions. For instance, [41] give an overview over various literature results: production costs are ranging from 273 USD/t to 2,106 USD/t. Besides technology assumptions, a major decisive factor is whether the production site is connected to the electricity grid or constitutes an isolated unit. As it is assumed in this report that the proposed system works in a standalone way, only studies with a comparable islanded design are considered.

[38] conducted a global analysis of islanded green ammonia production costs, only using solar and/or wind energy for electricity generation. Two different assumptions on interest rates are employed: uniform optimal interest rates applicable for a hypothetical multinational company (3.33% for electricity generation and 7.14% for the ammonia plant) and country-specific discount rates for domestic companies (e.g. 8.53% and 12.84% in the case of Ghana). For 2019, the average cost for the top 10 sites is 735 USD/t, while the global average

in the low interest case is 1,014 USD/t. The 2020 result of 903 USD/t displayed in Section IV-A is therefore at the upper end of the results from [38]. For the case of Ghana, [38] obtained costs of 770 USD/t and 1,173 USD/t for a multinational and domestic company, respectively. A different study by [42] simulated ammonia production on a process level. Minimal off-grid production costs for a solar-powered system were found at 842 €/t, in line with the results presented in this report. [43] also focused on solar energy, modeling off-grid large-scale ammonia production for a location in the United Arab Emirates. Production costs of 718 USD/t are calculated, lower than the costs obtained in this report, owing among other factors to very low electricity production costs of 0.025 USD/kWh compared to 0.039 USD/kWh for 2020 in the present analysis.

A key finding that is supported by various investigations found in literature is the high influence of electricity and hydrogen generation costs on ammonia production costs. For example, [38] state that hydrogen costs make up 58.2–71.4% of ammonia production costs in the 10 best sites per world region for 2019. As hydrogen electrolysis consumes most of the electricity, this value can be compared with the cost share of 72% for solar PV and hydrogen electrolysis, combined, as reported in Section IV-A. To enhance the cost-competitiveness of green fertilizers, it is therefore crucial to enable a low-cost supply of electricity as well as lowering the cost for hydrogen production equipment. Attractive costs of electricity generation can be achieved through a careful choice of location, potentially combining excellent solar and wind resources. Capital costs for electrolyzers can mainly be reduced through beneficial financing conditions, for example by attracting concessional finance. Furthermore, there is potential to generate additional revenue by selling excess electricity and the by-product oxygen.

B. Limitations

The present analysis gives a detailed overview of the production steps of green ammonia and its subsequent conversion to urea. There are several limitations to consider though. Firstly, the calculations only include the production of ammonia and urea, neglecting the following steps of the supply chain like storage and distribution as well as necessary additional infrastructure that potentially needs to be put in place, e.g. irrigation systems required for the aqueous ammonia route. Furthermore, as shown in Section IV-A, future cost developments of the needed components as well as the achievable discount rate play important roles in the overall cost calculation. Both of these factors are highly uncertain, given the fact that ammonia production powered by fluctuating renewable energy is a rather novel technology and that investments into lower income countries like Ghana tend to come with higher risk premiums.

VI. Conclusion

This work gives an insight into the cost-competitiveness of sustainable, decarbonized production of nitrogenous fertilizers, namely aqueous ammonia and urea, demonstrated in the Western African country of Ghana. Enhancing fertilizer access is considered a priority for Sub-Saharan Africa due to low crop yields which can be attributed to below-average fertilizer utilization [4]. Given the significant price surges in international fertilizer markets observed during recent years, local production could provide a more stable supply of fertilizers to Sub-Saharan Africa – both in terms of quantity and pricing. Additionally, the carbon-neutral production of ammonia and urea utilising solar energy and ambient air can significantly contribute to climate change mitigation, supporting global efforts for a net-zero world. As shown in this work, the sustainable production routes investigated are not yet competitive with conventional urea under normal market conditions. However, given expected future decreases in equipment costs, the economic position of sustainable fertilizers might substantially be enhanced in upcoming years. Considering that local green fertilizer production comes with the advantage of not being susceptible for disruptions in international markets, this price stability could make the deployment of such systems even more attractive. Further research has to be put into exploring the country-specific financial data and infrastructural needs to make use of this novel approach to fertilizer production as well as investigating the interaction of large-scale green ammonia production with the energy system. All in all, it can be stated that with the implementation of adequate policy measures, the domestic production of sustainable fertilizers has the potential to enhance farming conditions in Sub-Saharan Africa, increasing nutrient supply and fostering local value creation.

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