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Sustainable Urea Production and its Impact on Reducing CO_2 emissions in Arequipa, Perú

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***Abstract*—Currently, around 90% of synthetic fertilizers in Perú are imported, one of the most widely used being urea. The objective of this work is to present a urea production model coupled to two types of power plants based on the Peruvian energy matrix. Arequipa, a city in Perú, was considered a benchmark due to its diversified energy matrix. The proposed urea synthesis plant produces 15,768 tons of urea annually through an electricity-powered electrolysis process combined with carbon capture. The results showed that the urea production system requires 33.57 MW of electrical power, while the carbon capture system requires 1.47 kg/s of CO_2. A simplified economic assessment yielded a Levelized Cost of Urea (LCOU) of approximately 187 USD/t, while the proposed system achieved an energy efficiency of 59.6 kg urea/GJ. The CO_2 emissions that can be used as carbon credits from the solar photovoltaic power plant were higher than those generated by the thermoelectric power plant. These findings demonstrate the potential of Arequipa as a sustainable location for low-carbon urea production.**

***Index Terms*—Urea, Hydrogen, Energy transition, Emissions.**

I. Introduction

Agriculture in South America has shown a systematic growth trend over the last decades, mainly because of increased productivity, and demand not only in the region but also overseas [1],[2]. Specifically, the Peruvian economy is heavily based on agriculture and relies heavily on fertilizers, importing around 90% of synthetic fertilizers [3]. Fertilizers play an important role in ensuring sustainable agricultural production and food security around the world [4]. According to the International Fertilizer Industry Association (IFIA), Peru is responsible for around 600 to 700 kilo tons of nutrients per year, quantities that continue to grow [5]. Furthermore, the manufacture and transport of fertilizers to Perú represents a significant contribution to CO_2 emissions [6]. Also, the recent conflicts in the world have significantly impacted agricultural productivity of Peruvian farmers, as they have limited capacity to cope with price increases of fertilizers [3]. Therefore, in 2022 The Peruvian Ministry of Production created a multi-sectoral working group, a high-level commission for the creation and implementation of a national plant for urea and other nitrogen fertilizers to address the crisis of food security and family farming [7]. Then, in 2023 The Ministry of Energy and Mines in Peru approved the ministerial resolution that proposes the construction, installation and implementation of a phosphate rock fertilizer production plant in northern Peru, which will be the first plant of fertilizers processing in the country [8]. Although these initiatives will be of great help to the agricultural sector, due to the possibility of creating more processing plants in the country, it will be necessary to develop regulatory standards in relation to the fertilizer production and distribution chain, and subsequently the adaptation of fertilizer companies and enterprises in Peru to environmental and social sustainability criteria.

Through this, the consumption of nitrogen fertilizers represents more than 50% of the total fertilizers used in Perú [5]. Among chemical nitrogen fertilizers, urea is the most important on the market and one of the main sources of nitrogen supply for plants [9]. Currently, the synthesis of urea is a chemical process operated on an industrial scale. Traditionally, a urea production plant is built to complement an ammonia production plant. In the ammonia and urea production process, hydrogen is the most sought-after product because it does not exist freely in nature [10]. However, it is reported that 96% of commercially produced hydrogen in the world comes from fossil fuels, only 4% of global hydrogen production is obtained from water electrolysis [9].

Hydrogen is a promising energy and raw material carrier for decarbonizing the energy, transport and chemical sectors and mitigating the effects of global warming [11]. To produce hydrogen, different energy sources can be used, including renewable energy, natural gas, oil, nuclear energy and coal, but to claim green hydrogen, the entire production process must be carbon neutral [12]. Green hydrogen is generally produced through the electrolysis of water, where the energy source in the electrolyzer must be renewable energy [13]. Currently, Perú has a growing renewable energy in its electrical matrix as can be seen in Figure 1. Although the southern region of Peru has a high potential for the use of solar energy, due to the high irradiance in the area, growth in this area is slow, so the development of more solar projects will promote sustainability in the region [14].

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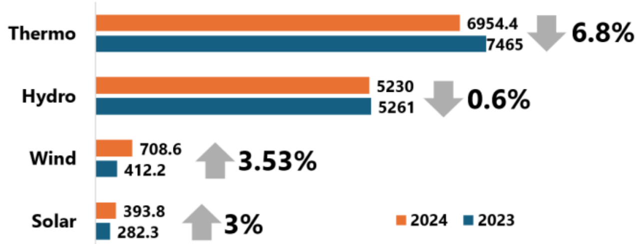

Fig. 1. Comparison of installed power in MW in the National Interconnected Electrical System of Peru (SEIN) between July 2023 and July 2024. Reproduced from [15].

To maintain a sustainable path, urea is preferably obtained from non-fossil fuel sources (called green urea). Until now, urea production based on renewable energy has been less economical than urea production based on fossil fuel power plants, so several technical, economic and environmental perspectives are needed in this area [16]. However, many research results have advocated green pathways for urea synthesis in sub-optimal ways, but which can be a sustainable solution for different contexts. Abbaspour et al. [17] proposed a hybrid cogeneration cycle to provide electricity and urea production. This system includes a combined gas and steam cycle, and a urea production system with an electrolyzer for hydrogen production. The proposed system produces 689 GWh of electrical energy and 1.323 million tons of urea annually. Ishaq et al. [18] proposed a system based on solar photovoltaic and wind energy with capture of carbon dioxide from the environment, production of hydrogen, urea and energy. The proposed project is capable of capturing 1387 tons of CO_2, producing 1894 tons of urea and 18.75 GWh annually. Gyanwali et al. [19] proposed a green urea production system composed of anaerobic digestion, gasification, decomposition of synthesis gas, with electrolysis of water to produce hydrogen. The system can produce 661 metric tons per day of green urea through the utilization of 962 metric tons per day of waste, along with the integration of an additional power source of 230 MW. Antonetti et al [20] carried out an economic and environmental impact analysis of a technology for producing urea from urban solid waste. The results showed that the proposed technology is economically and environmentally advantageous compared to conventional urea production technology (production with natural gas). Alfian & Purwanto [9] and Fernando & Purwanto [21] presented technical-economic perspectives on the potential for urea production through renewable energy sources. In general, renewable sources have growth potential according to each context, and their production costs are expected to decrease in the coming years. Galusnyak et al. [22] evaluated the technical and environmental performance of green and blue ammonia for urea production using process modeling tools and Life Cycle Assessment methodology. The results showed that green ammonia production needs greater energy consumption, but the inclusion of renewable energy sources can offer sustainable scenarios in the future. Zhang et al. [23] studied two green urea production processes (biomass and biomass with energy integrated) to evaluate the technical feasibility based on thermodynamic and economic performances in comparison with urea produced with methane. The results showed that methane production is more efficient, due to the high cost of energy in the study region. Kim et al. [24] performed technical analyses, itemized cost estimates, extended cost estimates, and life cycle assessment to produce renewable urea through alkaline water electrolysis. The results showed great technological advances in the area, which could offer solutions for green hydrogen production in the coming years. Devkota et al. [25] developed technical, economic and environmental analyses on the production of green urea by considering a hydroelectric power plant as an energy source. For their proposed plant, 220 kt/year will be produced, with total energy consumption of 8.18 PJ/year with the water electrolysis unit accounting for half of the energy demand. The environmental analysis showed the potential of the proposed green urea process as 326.11 kg CO_2/t of urea. It is concluded that lower hydroelectricity prices and carbon credit opportunities significantly improve the economic viability of the green urea production process.

The substitution of renewable energy sources for fossil fuels is a clear indication of the connection between sustainable urea production from green ammonia and the seventh Sustainable Development Goal (SDG), which is affordable and clean energy [26],[27]. In addition to helping with food production and forestation, which is in line with the goals of SDG 15—life on land—green urea is suggested to directly address SDG 13—climate action [13]. It is also important to note that the direct use of industrial or ambient CO_2 through carbon capture and storage in green urea production can result in carbon negative emissions.

Perú currently does not have sustainable urea production plants, but due to the recent initiatives, there is an expectation in the production and commercialization of fertilizers through sustainable paths. In addition, the growing renewable matrix in Peru seeks to project the implementation of new plants with a supply of clean energy, such as green hydrogen plants with water electrolysis using renewable energy. In fact, electrolyzer technology for hydrogen production is in constant development and is expected to have massive distribution in the coming years [28]. Specifically, Arequipa, a region in southern Peru, currently has electricity production led mainly by hydroelectric energy such as many regions in South America [29]. And due to the multiple initiatives at a global level, it plans to have the first green hydrogen plant in the country powered by a 1.8 GW solar facility, with the capacity to produce 80,000 tons of green hydrogen per year [30].

In this context, the objective of this study is to present two perspectives (thermoelectric and solar photovoltaic) for urea production and analyze their impacts on reducing CO_2 emissions in Arequipa, Perú. The results of the study can provide beneficial information for the implementation of sustainable urea plants in different regions in the southern Perú, depending on their energy facilities.

II. METHODOLOGY

A. Urea Production Modelling

Currently there are several technologies to produce urea, among them there are also some that have been modeled for sustainable production without fossil fuels [10]. In the present work, the synthesis of urea will include Cryogenic Air Separation Unit (CASU), Proton Exchange Membrane Electrolyzer (PEM), Ammonia System Reactor (ASR), Urea System Reactor (USR) and a source of CO_2. In ASR, hydrogen produced by water splitting in PEM reacts with nitrogen produced in CASU to produce ammonia. Urea is produced in the USR by reacting with the ammonia produced by the ASR and the CO_2 source, in addition to producing water. CO_2 is supplied by the carbon capture and storage system (CCS). Figure 2 shows the schematic diagram of the proposed cycle for urea production, where all the components will have a consumption of electric energy. Perú has an estimated consumption of 160 thousand tons of urea per year [5], which is approximately equivalent to 4.6 kg/s. A constant urea production of 2 kg/s was considered. A production rate of 2 kg/s was selected as a representative regional-scale facility, corresponding to approximately 15,768 tons/year, which represents nearly 10% of Peru's annual urea consumption. This capacity was adopted to evaluate the technical feasibility of local sustainable urea production in Arequipa rather than to replace the entire national demand. The water requirement for electrolysis is estimated at 1.79 kg/s, equivalent to approximately 14,100 m³/year assuming 6 h/day of operation. In the Arequipa region, this demand could be supplied by treated industrial or municipal water sources after appropriate purification for PEM electrolysis.

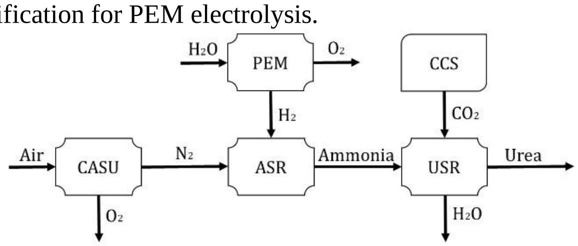

Fig. 2. Schematic diagram of the proposed urea production system

CASU is applied to produce pure nitrogen, oxygen and other gases that can be used in various industries [31]. The general reaction that occurs in this unit is as follows:

$$Air + Electricity \rightarrow 3.76N_2 + O_2 \quad (1)$$

Electric energy consumption according to current technology at CASU is 200 kWh per ton of molecular oxygen production, this value already includes the efficiency and energy losses of the equipment [32].

The PEM electrolyzer involves an input of electricity and water, providing outputs of hydrogen and oxygen [33]. This dissociation of water molecules can be represented by the following reaction:

$$H_2O + Electricity \rightarrow H_2 + 0.5O_2 \quad (2)$$

Due to changes in volumes, pressures and other irreversibilities in the electrolyzer, the net output energy of the electrolyzer is the change in Gibbs free energy [33]:

$$\Delta G = \Delta H - T\Delta S \quad (3)$$

Where ΔG (kJ/kmol) is the maximum output of a electrolyzer reaction (the movement of electrons in an external circuit), which is known as Gibbs free energy changes, ΔH (kJ/kmol) is the maximum output of heat of the electrolyzer, calculated based on the difference between enthalpy of the product and enthalpy of the reactant, ΔS (kJ/kmolK) is the entropy change and T (K) is the temperature of the electrolyzer. It is considered that the PEM electrolyzer operates as a closed system without mass losses. A PEM electrolyzer efficiency of 74% (higher heating value, HHV, basis) was adopted from Shaygan et al. [33]. According to Kumar et al. [34], PEM electrolyzer efficiencies are commonly reported on an HHV basis; therefore, the same basis was adopted in this study. The adopted efficiency corresponds to a specific electricity consumption of approximately 44.24 kWh/kg H_2, which is consistent with the electrical demand of 31.85 MW reported in Table II for a hydrogen production rate of 0.20 kg/s.

Currently, ammonia is mainly produced with the Haber-Bosch process, operated continuously at high temperature and pressure, i.e., 400–500 °C and 100–300 bar [16]. This chemical reaction is represented by the following equation:

$$N_2 + 3H_2 \rightarrow 2NH_3 + Heat \quad (4)$$

In the process of producing ammonia through the electrolysis of hydrogen. Approximately 95% of this energy is needed for hydrogen production and the remainder for nitrogen purification and ammonia synthesis [35]. Therefore, in the present case, the energy required by the USR will be considered to represent 2.5% of the energy for hydrogen production.

Urea is produced from the reaction of carbon dioxide and ammonia at high temperature and pressure. In the first stage, ammonium carbamate (NH_2COONH_4) is produced. It is then dehydrated to produce urea (NH_2CONH_2) [16]. These two reactions are shown below:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 + Heat \quad (5)$$

$$NH_2COONH_4 + Heat \rightarrow Urea + H_2O \quad (6)$$

The electrical energy required by USR was estimated using real data recently analyzed [36], obtaining 100 kWh per ton of urea. In this estimate, it was considered that the energy required for the USR is of the same order of magnitude as the ASR. Therefore, the power assigned to the USR represents the equivalent electrical demand required for gas compression, process operation, and the thermal energy associated with ammonia synthesis. In the proposed renewable configuration, no separate thermal energy source is considered, and all process energy requirements are assumed to be supplied by electricity, consistent with an all-electric production concept.

B. Modelling of power plants

This study was carried out by considering two power plants located in the southwest region of Arequipa, Perú. The first is the thermoelectric power plant Puerto Bravo and the second is the solar photovoltaic power plant Matarani, each of them with a different electrical substation (San José and Chaparral respectively) as shown in Figure 3. Puerto Bravo has four gas turbines, each of them with 180 MW (Installed capacity of 720 MW). Matarani has 147 120 photovoltaic panels, each of them with 650 Wp (Installed capacity of 80 MW).

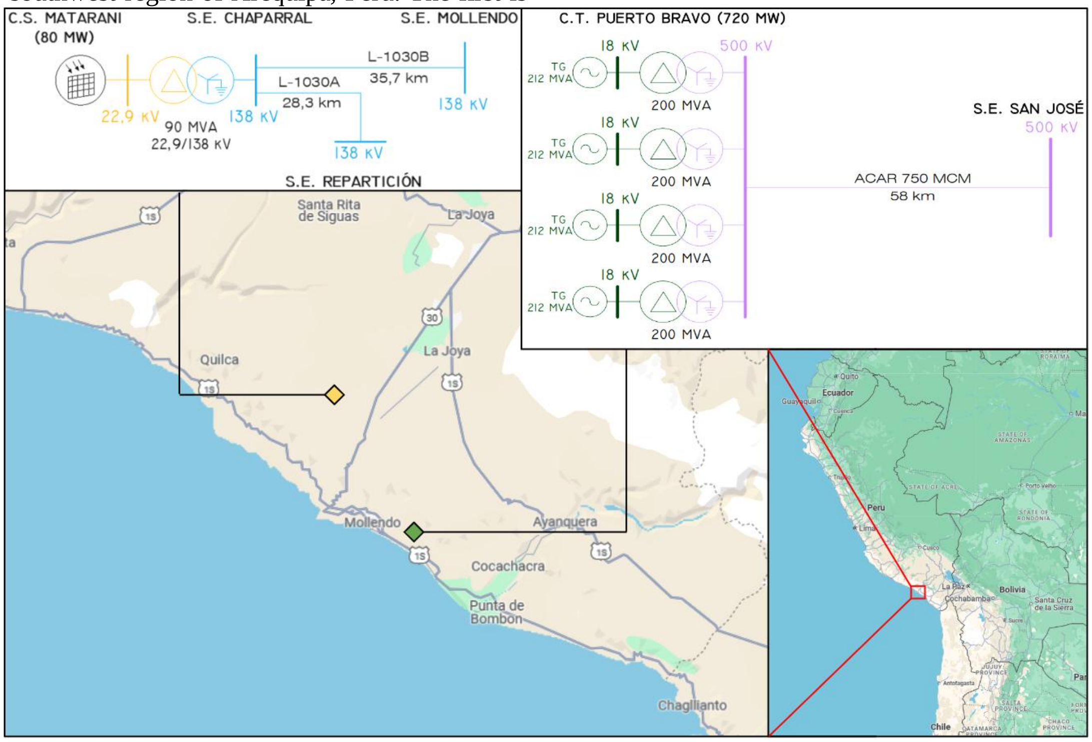

Fig. 3. Electrical diagram and location of power generation plants in Arequipa: Matarani (left) and Puerto Bravo (right). Reproduced from [37][38].

Figure 4 shows the schematic flowcharts of the power plants considered coupled to the urea production system. As the urea production system needs electrical energy, as well as CO_2, in the case of the renewable plant, direct air capture with CCS (DACCS) will be considered, and in the case of the gas plant carbon capture from gas turbines will be considered. For the thermoelectric configuration, CO2 is assumed to be captured from the flue gas of the Puerto Bravo power plant. For the photovoltaic configuration, CO2 is assumed to be supplied through Direct Air Capture (DAC). The effects of CO2 purity, compression requirements and capture energy consumption were not explicitly modeled. Therefore, the present assessment focuses on the mass requirements of CO2 for urea synthesis and should be interpreted as a preliminary evaluation.

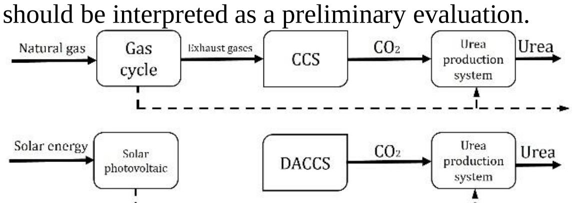

Fig. 4. Schematic flowcharts of the plants considered. The dotted lines represent the electrical energy supply.

C. Study of CO_2 emissions

The carbon footprint and the estimate of carbon credits are indicators used to study the impact of CO_2 emissions. Although the carbon footprint presents the quantity of emissions from a specific human or industrial process, the estimation of carbon credits presents a more pragmatic result that can offer benefits to an industry such as achieving its emission reduction objectives, improving its reputation, attracting customers and investors and supporting sustainable development [39]. However, it is necessary to have carbon footprint values to estimate carbon credits.

The CO_2 emissions from the thermoelectric power plant will be estimated using a recent empirical model, where the gas turbine operating parameters are relevant [40] shown in eq. 7.

$$\dot{m}_{CO_2} = 0.000365t - 0.00478\varphi - 5.272583r_p \\ -0.000546\dot{m}_g + 83.734 \tag{7}$$

Where t is the ratio between turbine inlet temperature and ambient temperature, φ is the relative humidity of ambient air, r_p is the pressure ratio of compressor and $\dot{m}g$ is the exhaust gas mass flow rate. With environmental parameters: air temperature of 20°C, pressure 101,3 kPa, and relative humidity of 75%. The operational parameters for the gas turbine operation are listed in Table I. Finally, the quantities of CO_2 emission on each carbon credit type for the two power plant configurations used for urea production will be presented.

TABLE I.
OPERATION PARAMETERS FOR EACH GAS TURBINE IN PUERTO BRAVO THERMOELECTRIC POWER PLANT [41]

Parameter	Value	Unit
Net Power	180	MW
Specific consumption	9582	kJ/kWh
Gas turbine inlet temperature	1773	K
Pressure ratio of compressor	15	-
Calorific value of natural gas	53000	kJ/kg
Exhaust gas mass flow rate	516	kg/s

III. RESULTS

The mass balance and energy required in the urea production process are presented in Table II for a constant urea production of 2 kg/s. The electrical energy required by the system is 33.57 MW. So, in the case of the system with the thermoelectric power plant, there is a useful power of 686.43 MW. In the case of the photovoltaic power plant, there is a useful power of 46.43 MW. The proposed photovoltaic-based configuration assumes an effective operation period of approximately 6 h/day according to the solar resource availability in the region. Although the PEM electrolyzer can operate under variable loads, ammonia and urea synthesis units are typically designed for steady-state operation. Therefore, continuous operation of the complete production chain would require additional energy management strategies such as battery energy storage systems, hydrogen storage, or grid support. These aspects were not explicitly modeled in the present work and should be evaluated in future studies to assess the feasibility of continuous industrial-scale operation. It can be distinguished that in the process of producing ammonia and, consequently, urea, obtaining hydrogen in the PEM requires most of the electrical energy. Likewise, throughout this process, there are some secondary resources that resulted from the obtaining of others such as oxygen or ammonium carbamate, so it would be appropriate to plan their use or commercialization in another productive sector.

TABLE II.
MASS BALANCE AND POWER REQUIRED IN UREA PRODUCTION

Equipment	Component	M.W. (g/mol)	Mass flow (kg/s)	Power (kW)
CASU	Air	28.96	1.21	201.60
	0.210 O_2	6.72	0.28	
	0.794 N_2	22.24	0.93	
PEM	H_2O	18.01	1.79	31853.25
	0.5 O_2	16.00	1.59	
	H_2	2.01	0.20	
ASR	N_2	28.01	0.93	796.33
	3 H_2	6.05	0.20	
	2 NH_3	34.06	1.13	
USR	2 NH_3	34.06	1.13	720.00
	CO_2	44.01	1.47	
	NH_2COONH_4	78.07	2.60	
	H_2O	18.01	0.60	
	Urea	60.06	2.00	

In the case of the thermoelectric power plant, the estimated CO_2 emissions for each turbine are 4.36 kg/s, but only 1.47 kg/s of CO_2 emissions are captured. By considering a continuous production of urea for 6 hours per day, then it will obtain an annual production of urea of 15768 tons and annual capture of 11589.48 metric tons of CO_2. However, the most appropriate option would be to be able to capture all the CO_2 emitted by the power plant. Today there are other sub-processes that require CO_2, as well as the possibility of capturing it to sell it on the carbon market. However, in many countries of South America there is the absence of a concrete policy structure to promote net-zero emissions technologies, as well as legislation for the carbon market [42]. Current state of art on carbon capture technologies is very promising, furthermore its implementation should be well defined and limited through national regulations [43]. For the photovoltaic power plant, it is estimated the greenhouse gasses emission reduction for annual energy generated in these power plants [44]. Considering at least 6 hours of continuous generation per day, it will have around an annual energy generated of 175.2 GWh, then 124255.32 metric tons of CO_2 equivalent per year are obtained through the CO_2 equivalences of the U.S. Environmental Protection Agency [45].

A simplified economic assessment was performed through the estimation of the Levelized Cost of Urea (LCOU). Since the PEM electrolyzer represents approximately 95% of the total electricity consumption of the proposed plant, electricity cost was considered as the dominant operational expenditure. Capital expenditures (CAPEX), maintenance costs, labor costs, financing costs and carbon credit revenues were not included in this preliminary assessment. Therefore, the resulting LCOU should be interpreted as a first-order economic indicator rather than a complete techno-economic evaluation.

TABLE III.
SIMPLIFIED LCOU ESTIMATION

Parameter	Value
Electrical demand	33.57 MW
Operating hours	2190 h/year
Annual electricity consumption	73.52 GWh/year
Electricity price	0.04 USD/kWh
Annual electricity cost	2.94 million USD/year
Annual urea production	15768 ton/year
Simplified LCOU	187 USD/ton urea

The simplified LCOU estimation is shown in Table III. The estimated annual electricity consumption of the proposed plant is approximately 73.52 GWh/year. Assuming an industrial electricity price of 0.04 USD/kWh, representative of the levelized cost of electricity (LCOE) of utility-scale renewable energy projects reported by IRENA [46], the annual operating cost associated with electricity is estimated at 2.94 million USD/year. Under these assumptions, the simplified LCOU reaches approximately 187 USD per ton of urea. This result indicates that electricity availability and electricity price are the most influential parameters affecting the economic viability of green urea production. Consequently, regions such as Arequipa, which present high solar irradiation potential and increasing renewable energy deployment, may offer favorable conditions for future sustainable urea production facilities.

For comparison, the average CIF import price of urea in Peru was approximately 413 USD/t in 2024, whereas the simplified LCOU estimated in this study is 187 USD/t. This preliminary comparison indicates that electricity costs alone would not prevent the economic competitiveness of local green urea production, although a complete techno-economic assessment including CAPEX and other operating expenditures is still required [47].

The obtained value is within the same order of magnitude reported in recent studies on green urea production based on renewable energy sources. Devkota et al. [25] highlighted that electricity cost is one of the most critical factors influencing the competitiveness of green urea systems. Therefore, future reductions in renewable electricity costs and advances in electrolyzer technology are expected to further improve the economic feasibility of the proposed concept. The present assessment assumes an effective operation of 6 hours per day according to the available solar generation period. Continuous operation through energy storage systems, hydrogen storage or grid balancing strategies was not considered and should be evaluated in future studies.

The energy efficiency of the proposed system was estimated at 59.6 kg urea/GJ based on the total electrical demand and annual urea production. For comparison, Devkota et al. [25] reported a specific energy consumption of 36.69 GJ/t urea, corresponding to approximately 27.3 kg urea/GJ. However, this comparison should be interpreted with caution because Devkota et al. included the energy required for CO_2 capture and plant utilities, whereas the present study excludes the energy associated with CO_2 capture, compression, and purification. Consequently, including these additional energy requirements would reduce the reported energy efficiency of 59.6 kg urea/GJ. Direct comparison with Abbaspour et al. [17] and Ishaq et al. [18] is challenging because these studies primarily report energy generation and product outputs rather than specific energy consumption values.

Carbon Credits are classified into two types: “Carbon Offset Credits” (COCs) and “Carbon Reduction Credits” (CRCs). COCs are made up of sustainable energy sources such as wind, solar, hydro and biofuels. While CRCs are efforts to collect and store carbon from our atmosphere through biosequestration, such as reforestation and afforestation, collection and storage in the ocean and soil. Both approaches are considered effective methods for reducing the global carbon emissions “crisis” [48]. Following the Kyoto protocol, “The UN Framework Convention on Climate Change” (UNFCCC) developed the “Clean Development Mechanism” (CDM) standard, which introduces the calculation of carbon certificates [49]. In the case of the plant model operating with renewable energy (without CO_2 emissions), both types of carbon credits would be relevant, both for the implementation of a renewable energy plant and for capturing CO_2 emissions from the air. Emissions reductions achieved by the renewable energy project are typically achieved by comparing emissions from a reference case (in this case, a thermoelectric plant) with emissions from the renewable energy project, the thermoelectric power plant will have a CO_2 emission intensity of 0.0218 kgCO_2/KWh, so the annual CO_2 emission through this analysis for the solar photovoltaic will be 3819.36 of metric tons of CO_2. Also, in this case we will also consider the quantity of emissions reduced through the CO_2 equivalences from EPA. In the case of the thermoelectric power plant model, credits would only be considered for the CO_2 emissions captured for urea production.

Table IV shows the comparison of the CO_2 equivalents differentiated by the type of carbon credits over a period of one year. The carbon credits by considering EPA carbon trade in the photovoltaic power plant are almost 10 times greater than the credits in the thermoelectric power plant. While, by using the CO_2 reduction taken as a reference the thermoelectric power plant, this value will be reduced. This indeed depends a lot on how the regulations were planned for each carbon market, as well for carbon footprint legislations in each country. However, this value may be more competitive in the thermoelectric power plant when the remaining CO_2 captured can be used or sold. Likewise, the reference value for estimating carbon credits in the case of plants with renewable sources may be different, depending on the characteristics of the power plant and legislation. The values obtained with carbon credits offer a very favorable long-term reference for both perspectives. Since countries in South America await its prompt creation and accession to the carbon market, or in any case, possible participation of Peruvian companies in international carbon markets. It is important to highlight that some regions such as Arequipa have an advantageous position to produce low-cost raw materials with no emissions during the process. This is due to the possibility of implementation of solar photovoltaic projects, combined with the diverse renewable electrical matrix and its geographic position.

TABLE IV.
METRIC TONS OF CO_2 EQUIVALENT PER YEAR CONSIDERED AS CARBON CREDIT FOR EACH POWER PLANT.

Carbon credit type	Thermoelectric power plant	Solar photovoltaic power plant
COCs	-	124255.32 (EPA) 3819.36 (Ref.)
CRCs	11589.48	11589.48

IV. CONCLUSION

In this work, a urea production system is proposed with two different sources of electrical energy supply to analyze the impact of CO_2 emissions in a southwest region in Arequipa, Perú. This system considers the Haber-Bosch process for producing ammonia, with hydrogen obtained through an electrolyzer and nitrogen obtained by air separation. Finally, the production of urea is based on the reaction of ammonia with carbon dioxide in a reactor. The proposed system produces 2 kg/s of urea, annually producing 15768 tons of urea, with an electrical energy requirement of 33.57 MW. Hydrogen production represents almost 95% of the electrical energy needed. The proposed project is capable of capturing 1.47 kg/s of CO_2. An estimate of the value of CO_2 emission according to the “Clean Development Mechanism” standard, as it presents some considerations regarding the classification of carbon credits. In the case of the thermoelectric power plant, CO_2 emissions were quantified through an empirical model in the power plant chosen for the study. These CO_2 emissions for the solar photovoltaic power plant were estimated with CO_2 equivalences from EPA. For both cases very favorable results were obtained considering a constant production of urea for one year. A simplified economic assessment yielded an estimated LCOU of approximately 187 USD/ton of urea, indicating that electricity cost remains the dominant parameter affecting economic viability. This analysis represents the case of urea production considering carbon capture and the use of electricity from renewable and fossil sources in Arequipa, Perú but can be adapted to the production of raw materials with other industrial processes.

Author Contributions

Jose Canazas Rodriguez: Conceptualization, numerical modelling, formal analysis, manuscript writing, data interpretation.

Yuri Silva Vidal: Supervision, methodology review, manuscript editing, validation, and final approval of manuscript

AI Tool Usage Acknowledgment

Artificial Intelligence (AI)-based language assistance tools were utilized for grammatical refinement and language improvement.

Conflict of Interest

The authors have no conflicts of interest to declare.

Declaration of Funding

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References

[1] V. Zalles, M. C. Hansen, P. V. Potapov, D. Parker, S. V. Stehman, A. H. Pickens, L. L. Parente, L. G. Ferreira, X.-P. Song, A. Hernandez-Serna, and I. Kommareddy, "Rapid expansion of human impact on natural land in South America since 1985," Science Advances, vol. 7, no. 14., 2021, doi: 10.1126/sciadv.abg1620

[2] A. F. Dias Avila, L. Romano, and F. Garagorry, "Chapter 71 Agricultural Productivity in Latin America and the Caribbean and Sources of Growth," in Handbook of Agricultural Economics, Elsevier, 2010, pp. 3713–3768. doi: 10.1016/S1574-0072(09)04071-7

[3] M. Nacimento, "The Russia-Ukraine War and the Peruvian Agrarian Crisis," Bulletin of Latin American Research, vol. 43, no. 4, pp. 340–343, 2024. doi: 10.1111/blar.13592.

[4] N. Yahya, "Urea Fertilizer: The Global Challenges and Their Impact to Our Sustainability," in Green Energy and Technology. Springer, 2018, pp. 1–21. doi: 10.1007/978-981-10-7578-0_1

[5] International Fertilizer Association (IFA) (2021) Consumption Report by country. IFA [Online]. Available: https://www.ifastat.org/databases/plant-nutrition

[6] S. Menegat, A. Ledo, and R. Tirado, "Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture," Scientific Reports, vol. 12, no. 1., 2022. doi: 10.1038/s41598-022-18773-w.

[7] Ministerio de la Producción. (2022, Sep.). Resolución Suprema N.° 015-2022-PRODUCE. [Online]. Available: https://www.gob.pe/institucion/produce/normas-legales/3426860-015-2022-produce

[8] Ministerio de Energía y Minas. (2023, Nov.). Resolución Ministerial N.° 449-2023-MINEM/DM. [Online]. Available: https://www.gob.pe/institucion/minem/normas-legales/4872826-449-2023-minem-dm

[9] M. Alfian and W. W. Purwanto, "Multi-objective optimization of green urea production," Energy Science & Engineering, vol. 7, no. 2., pp. 292–304, 2019. doi: 10.1002/ese3.281

[10] D. Milani, A. Kiani, N. Haque, S. Giddey, and P. Feron, "Green pathways for urea synthesis: A review from Australia's perspective," Sustainable Chemistry for Climate Action, vol. 1, p. 100008, 2022. doi: 10.1016/j.scca.2022.100008.

[11] M. Hermesmann and T. E. Müller, "Green, Turquoise, Blue, or Grey? Environmentally friendly Hydrogen Production in Transforming Energy Systems," Progress in Energy and Combustion Science, vol. 90, p. 100996, May 2022. doi: 10.1016/j.pecs.2022.100996.

[12] M. G. Rasul, M. A. Hazrat, M. A. Sattar, M. I. Jahirul, and M. J. Shearer, "The future of hydrogen: Challenges on production, storage and applications," Energy Conversion and Management, vol. 272, p. 116326, 2022. doi: 10.1016/j.enconman.2022.116326.

[13] C. Mao, J. Byun, H. W. MacLeod, C. T. Maravelias, and G. A. Ozin, "Green urea production for sustainable agriculture," Joule, vol. 8, no. 5, pp. 1224–1238, 2024. doi: 10.1016/j.joule.2024.02.021.

[14] C. Cacciuttolo, X. Guardia, and E. Villicaña, "Implementation of Renewable Energy from Solar Photovoltaic (PV) Facilities in Peru: A Promising Sustainable Future," Sustainability, vol. 16, no. 11, p. 4388, 2024. doi: 10.3390/su16114388.

[15] Asociación Peruana de Energías Renovables (SPR). (2024, Jul.). Reporte Estadístico Sector Elíctrico. [Online]. Available: https://www.spr.pe/wp-content/uploads/2024/09/SPR-informe-estadistico-mensual-Julio-2024-2.pdf

[16] H. Kim, A. Lee, and H. Lim, "Decision making with the deterministic judgment of urea production with various hydrogen sources: technical, economic, and environmental aspects," Green Chemistry, vol. 24, no. 21, pp. 8412–8423, 2022. doi: 10.1039/d2gc01936a.

[17] H. Abbaspour, M. A. Ehyaei, A. Ahmadi, M. Panahi, A. Abdalisousan, and A. Mirzohosseini, "Energy, exergy, economic, exergoenvironmental and environmental (5E) analyses of the cogeneration plant to produce electrical power and urea," Energy Conversion and Management, vol. 235, p. 113951, 2021. doi: 10.1016/j.enconman.2021.113951.

[18] H. Ishaq, O. Siddiqui, G. Chehade, and I. Dincer, "A solar and wind driven energy system for hydrogen and urea production with CO_2 capturing," International Journal of Hydrogen Energy, vol. 46, no. 6, pp. 4749–4760, 2021. doi: 10.1016/j.ijhydene.2020.01.208.

[19] K. Gyanwali, S. Karki, P. Adhikari, S. Devkota, and P. Aryal, "Techno-economic assessment of green urea production utilizing municipal solid waste and hydropower in Nepal," Journal of Cleaner Production, vol. 419, p. 138320, 2023. doi: 10.1016/j.jclepro.2023.138320.

[20] E. Antonetti, G. Iaquaniello, A. Salladini, L. Spadaccini, S. Perathoner, and G. Centi, "Waste-to-Chemicals for a Circular Economy: The Case of Urea Production (Waste-to-Urea)," ChemSusChem, vol. 10, no. 5, pp. 912–920, 2017. doi: 10.1002/cssc.201601555.

[21] C. Fernando and W. W. Purwanto, "Techno-economic analysis of a small-scale power-to-green urea plant," IOP Conference Series: Earth and Environmental Science, vol. 716, no. 1, p. 012010, 2021. doi: 10.1088/1755-1315/716/1/012010.

[22] S. C. Galusnyak, L. Petrescu, V.-C. Sandu, and C.-C. Cormos, "Environmental impact assessment of green ammonia coupled with urea and ammonium nitrate production," Journal of Environmental Management, vol. 343, p. 118215, 2023. doi: 10.1016/j.jenvman.2023.118215.

[23] H. Zhang, L. Wang, J. Van herle, F. Maréchal, and U. Desideri, "Techno-economic comparison of 100% renewable urea production processes," Applied Energy, vol. 284, p. 116401, 2021. doi: 10.1016/j.apenergy.2020.116401.

[24] H. Kim, C. Choe, A. Lee, and H. Lim, "Application of green hydrogen with theoretical and empirical approaches of alkaline water electrolysis: Life cycle-based techno economic and environmental assessments of renewable urea synthesis," International Journal of Hydrogen Energy, vol. 48, no. 43, pp. 16148–16158, 2023. doi: 10.1016/j.ijhydene.2023.01.062.

[25] S. Devkota, P. Karmacharya, S. Maharjan, D. Khatiwada, and B. Uprety, "Decarbonizing urea: Techno-economic and environmental analysis of a model hydroelectricity and carbon capture based green urea production," Applied Energy, vol. 372, p. 123789, 2024. doi: 10.1016/j.apenergy.2024.123789.

[26] S. Nand and M. Goswami, "Prospects of Green Ammonia in Fertilizer Production," Green Energy and Technology, pp. 303–309, 2024. doi: 10.1007/978-981-99-6237-2_16.

[27] G. Pagani, Y. Hajimolana, and C. Acar, "Green hydrogen for ammonia production – A case for the Netherlands," International Journal of Hydrogen Energy, vol. 52, pp. 418–432, 2024. doi: 10.1016/j.ijhydene.2023.06.309.

[28] A. Franco and C. Giovannini, "Recent and Future Advances in Water Electrolysis for Green Hydrogen Generation: Critical Analysis and Perspectives," Sustainability, vol. 15, no. 24, p. 16917, 2023. doi: 10.3390/su152416917.

[29] D. G. De la Cruz Torres, L. F. Mazadiego, D. Bolonio, and R. R. Pons-Esparver, "Long-Term Forecast of Energy Demand towards a Sustainable Future in Renewable Energies Focused on Geothermal Energy in Peru (2020–2050): A LEAP Model Application," Sustainability, vol. 16, no. 12, p. 4964, 2024. doi: 10.3390/su16124964.

[30] Energiminas. (2024, Sep.). Arequipa tendrá la planta de hidrógeno verde más grande de Sudamérica, afirma su gobernador regional. [Online]. Available: https://energiminas.com/2024/09/20/arequipa-tendra-la-planta-de-hidrogeno-verde-mas-grande-de-sudamerica-afirma-su-gobernador-regional/

[31] S. Tesch, T. Morosuk, and G. Tsatsaronis, "Comparative Evaluation of Cryogenic Air Separation Units from the Exergetic and Economic Points of View," in Low-temperature Technologies, IntechOpen, 2020. doi: 10.5772/intechopen.85765.

[32] T. Banaszkiewicz, M. Chorowski, and W. Gizicki, "Comparative Analysis of Oxygen Production for Oxy-combustion Application," Energy Procedia, vol. 51, pp. 127–134, 2014. doi: 10.1016/j.egypro.2014.07.014.

[33] M. Shaygan, M. A. Ehyaei, A. Ahmadi, M. E. H. Assad, and J. L. Silveira, "Energy, exergy, advanced exergy and economic analyses of hybrid polymer electrolyte membrane (PEM) fuel cell and photovoltaic cells to produce hydrogen and electricity," Journal of Cleaner Production, vol. 234, pp. 1082–1093, 2019. doi: 10.1016/j.jclepro.2019.06.298.

[34] S. Sood, O. Prakash, M. Boukerdja, J.-Y. Dieulot, B. Ould-Bouamama, M. Bressel, and A.-L. Gehin, "Generic Dynamical Model of PEM Electrolyser under Intermittent Sources," Energies, vol. 13, no. 24, p. 6556, 2020. doi: 10.3390/en13246556.

[35] K. H. R. Rouwenhorst and L. Lefferts, "Feasibility Study of Plasma-Catalytic Ammonia Synthesis for Energy Storage Applications," Catalysts, vol. 10, no. 9, p. 999, 2020. doi: 10.3390/catal10090999.

[36] L. Fiamelda, Suprihatin, and Purwoko, "Analysis of water and electricity consumption of urea fertilizer industry: case study PT. X," IOP Conference Series: Earth and Environmental Science, vol. 472, no. 1, p. 012034, 2020. doi: 10.1088/1755-1315/472/1/012034.

[37] Organismo Supervisor de la Inversión en Energía y Minería (2024, Aug.). Supervisión de contratos de proyectos de generación y transmisión de energía eléctrica en operación. [Online]. Available: https://www.osinergmin.gob.pe/seccion/centro_documental/electricidad/Documentos/Publicaciones/Compendio-Proyectos-GTE-Operacion.pdf

[38] Comité de Operación Económica del Sistema Interconectado Nacional (2024. Sep.). Lineas existentes del Sistema Interconectado Nacional. [Online]. Available: https://www.coes.org.pe/portal/browser/download?url=Operaci%C3%B3n%2FCaracteristica%20del%20SEIN%2FMapa%20del%20SEIN%2F2024%2F09_SETIEMBRE%2FLineas%20ExistentesCOES_SETIEMBRE%202024.pdf

[39] D. Pandey, M. Agrawal, and J. S. Pandey, "Carbon footprint: current methods of estimation," Environmental Monitoring and Assessment, vol. 178, no. 1–4, pp. 135–160, 2010. doi: 10.1007/s10661-010-1678-y.

[40] H. O. Egware and C. C. Kwasi-Effah, "A novel empirical model for predicting the carbon dioxide emission of a gas turbine power plant," Heliyon, vol. 9, no. 3, p. e14645, 2023. doi: 10.1016/j.heliyon.2023.e14645.

[41] C. A. Gordillo, "Análisis termodinámico de una Central Termoeléctrica de ciclo combinado Gas - Vapor con el Programa EES", Doctoral Dissertation. Universidad Nacional de San Agustin, Arequipa, Perú, 2019.

[42] F. U. M. Allah, A. da S. Marques, and M. Carvalho, "Current status, challenges and future prospects of carbon capture and storage (CCS) for thermal power plants in Brazil," International Journal of Greenhouse Gas Control, vol. 136, p. 104198, 2024. doi: 10.1016/j.ijggc.2024.104198.

[43] M. Rogieri Pelissari, S. San Martín Cañas, M. Oliveira Barbosa, and C. C. Gaeta Tassinari, "Decarbonizing coal-fired power plants: Carbon capture and storage applied to a thermoelectric complex in Brazil," Results in Engineering, vol. 19, p. 101249, 2023. doi: 10.1016/j.rineng.2023.101249.

[44] Y. Aziz, A. K. Janjua, M. Hassan, M. Anwar, S. Kanwal, and M. Yousif, "Techno-economic analysis of PV systems installed by using innovative strategies for smart sustainable agriculture farms," Environment, Development and Sustainability, vol. 26, no. 2, pp. 5003–5024, 2023. doi: 10.1007/s10668-023-02919-5.

[45] U.S. Environmental Protection Agency. (2024). Greenhouse gases Equivalencies calculator-calculations and references. [Online]. Available: https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

[46] International Renewable Energy Agency (IRENA). (2025). Renewable Power Generation Costs in 2024. Abu Dhabi: IRENA. [Online]. Available: https://www.irena.org/Publications/2025/Jun/Renewable-Power-Generation-Costs-in-2024

[47] World Integrated Trade Solution (WITS). (2025). Peru Imports of Urea (HS 310210). World Bank. [Online]. Available: https://wits.worldbank.org/trade/comtrade/en/country/PER/year/2024/tradeflow/Imports/partner/ALL/product/310210

[48] G. Velvizhi, R. Nair, C. Goswami, S. K. Arumugam, N. P. Shetti, and T. M. Aminabhavi, "Carbon credit reduction: A techno-economic analysis of 'drop-in' fuel production," Environmental Pollution, vol. 316, p. 120507, 2023. doi: 10.1016/j.envpol.2022.120507.

[49] M. Gillenwater and S. Seres, "The Clean Development Mechanism: a review of the first international offset programme," Greenhouse Gas Measurement and Management, vol. 1, no. 3–4, pp. 179–203, 2011. doi: 10.1080/20430779.2011.647014.

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