Techno-Economic and Environmental Analysis of Blue Ammonia Production: Simulation Study

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**Abstract.** Decarbonization of ammonia industry is often considered as an important step to reduce emissions from Industrial Process and Product Use (IPPU) sector. One way to do this is by integrating carbon capture and storage (CCS) technology with ammonia industry to produce blue ammonia. This study aims to evaluate the economic and environmental impact of blue ammonia production compared to conventional grey ammonia in Indonesia. Here, we performed simulation of CO2 capture from flue gases of an ammonia plant with Aspen HYSYS with capture efficiency of 99.6%. Our study shows that the levelized cost of blue ammonia is 54% higher than the of grey ammonia. Further, we also found an increase in CAPEX and OPEX values by 105% and 48% due to additional investment for CCS. The results from Life Cycle Assessment (LCA) showed that blue ammonia gave Global Warming Potential (GWP) impact of 0.787 ton CO2/ton NH3 while grey ammonia gave 2 ton CO2/ton NH3. Hence, with proper incentive, we believe that production of blue ammonia from existing ammonia plants can be an attractive option to lower their emission during the energy transition period.

# INTRODUCTION

Ammonia is one of the essential forms of nitrogen and hydrogen. According to the International Energy Agency (IEA) in 2021, ammonia consumption will be predominantly driven by urea fertilizer production (70%), and the remaining 30% will be utilized in manufacturing synthetic fibers, plastics, and explosives. The ammonia demand is projected to maintain its upward trajectory, soaring from an initial 235 million tons in 2019 to an estimated 360 million tons by 2030 [1]. In 2019, Indonesia was the fifth-greatest global ammonia producer. However, Greenhouse Gas (GHG) emissions will grow proportionally with the rise in ammonia production.

Ammonia produced through the Haber-Bosch process consumes hydrogen from natural gas and nitrogen from the air, this ammonia as we are known as grey ammonia [2]. While, the production of ammonia from natural gas is a well- established process, it still presents several challenges, primarily greenhouse gas (GHG) emissions. These GHGs can originate from the natural gas feedstock itself (Harnisch et al., 2006), as well as from the cO2 removal unit. Various studies have indicated that the GHG emissions associated with ammonia production from natural gas range from 1.9 to 2.6 tons of CO2 per ton of ammonia produced (mckinsey.com). Notably, 90% of these CO2 emissions occur during the SMR process (Royal Society, 2020).

The Ministry of Environment and Forestry (LHK) reported that the industrial processes and product use (IPPU) sector generated 59,192 Gg of CO2e in 2022, with the ammonia industry accounting for 15% of this total at 9,128 Gg CO2e. Recognizing the substantial GHG emissions associated with ammonia production, the government has

designated the ammonia industry as a priority sector for national GHG mitigation initiatives. The process is energy- incentive and produces GHG emissions from using natural gas as raw material, as well as from the burning of CO2 gas, and the operation of CO2 removal systems. In ammonia industry generates 1.9 – 2.6 MT CO2/ton NH3 (mckinsey.com), and of its CO2 emissions through the Steam-Methane Reforming (SMR) process, a hotspot for emissions [3].

In the Enhanced Indonesian Nationally Determined of Contributions (NDC) document for 2022, Indonesia aims to decrease GHG emissions in the ammonia industry by establishing a reduction target of 3.95 million tons of CO2 and 4.65 million tons of CO2 with international assistance, and the mitigation actions carried out in ammonia industries are (i) revitalization of ammonia plants to reduce natural gas consumption intensity, (ii) increase plant efficiency and reduce IPPU emissions, and (iii) CO2 utilization [4]. An alternative solution is integrating Carbon Capture and Storage (CCS) technology into the ammonia sector, and some countries, implementing CCS technology to reduce their CO2 emissions [5].

The Ministry of Energy and Mineral Resources (ESDM) reported in 2023 that Indonesia, especially in the oil and gas industry has 15 projects to develop CCS technology, and in the fertilizer sector, Pupuk Indonesia, plans to develop seven blue ammonia projects across its various facilities in Aceh, east Kalimantan, south Sumatra, and east Java. The company is currently the largest grey ammonia producer in Asia, produced from natural gas without any CCS, with a total production capacity of 7 mn MT/yr. It will convert its existing grey plants to blue ammonia facilities with the implementation of CCS, targeting a total of 4.3 mn MT/yr of blue ammonia production by 2045.

CCS is a technology capable of capturing carbon emissions from the air and storing them in a storage facility with carbon emissions directed and injected into old oil and gas wells. The fertilizer sector in Indonesia plans to use CCS at five potential sites comprising the Arun field, east Kalimantan, Sunda Asri basin, Gundih, and Sukowati, with expecting potential CCS use to gradually increase to 4.3 mn t of carbon dioxide (CO2) by 2045, as part of its efforts to decarbonize ammonia and fertilizer products, while expanding into new market of blue ammonia.

CCS technology is added to the SMR and CO2 Removal Units (CRU) process, as the most significant emission hotspot; the ammonia produced from CCS technology is called blue ammonia [6]. CCS technology involves separating, transporting, and injecting CO2 (esdm.go.id). In addition to being used as an alternative to mitigation efforts, integrating CCS technology can benefit the industry if the Indonesian government establishes regulations regarding carbon taxes. In integration, other benefits can be obtained by providing incentives for CCS implementation by laws and regulations, however, the Ministry of Energy and Mineral Resources still considers the tax mechanism, carbon trading, and incentives.

Based on these considerations, the integration of CCS technology in the ammonia industry needs to be developed, especially from the economic and environmental sectors. Currently, Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA) are tools that are widely used in the early stages of technology development as a step to evaluate the economic feasibility and environmental performance in the future. This study aims to address the lack of detailed techno-economic and environmental assessments of blue ammonia production in Indonesia by performing a simulation of an ammonia plant with integrated CCS.

# METHODS

This study was carried out in three stages. The first stage determined the efficiency of the capturing equipment simulated using Aspen HYSYS. The second stage calculated the techno-economic, and the third or last stage calculated the environmental impact using OpenLCA software.

## Methodology for simulation

* 1. *Process selection*

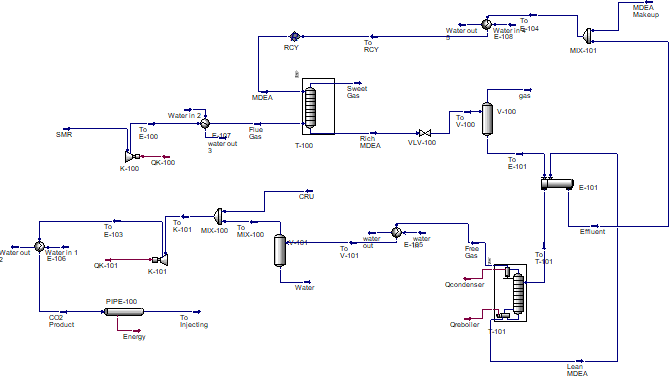
Several processes are available for acid gas purification, all suitable depending on the available conditions. This study uses a technology absorber-stripper for CO2 capture, with 56% Methyl Diethanolamine (MDEA) as a chemical solvent

[7] and the flow rate of flue gas is 275,773.243 kg/h combined from SMR and CRU. CO2 capture using aqueous alkanolamine solution by absorption process was proven to be effective in removing CO2 gas from flue gas of various industries [8].

* 1. *Process description*

Fig. 1 shows flue gas from SMR has to be compressed, in this process it is also necessary to increase the temperature significantly, so it is necessary to reduce temperature using a heat exchanger before entering the absorption process.

Absorption process by contacting solvent in the form of MDEA with a concentration of 56%, the solvent absorbs the acid gases, and the sweet gas leaves the segment from the top. The rich amine is then sent to the valve and separated from N2 with a flash tank to lower the pressure. Then, the rich amine is warmed through the heat exchanger, this amine is stripped off CO2 at low pressure and high temperature in the regenerator. The acid gas and some water leave the generator through an overhead condenser.



**FIGURE 1.** Simulation flow sheet of capturing processes

This lean amine leaves the base of the regenerator through the heat exchanger and blends with the warm water and amine (stream effluent). Then, the lean amine is recycled to the stream MDEA, cooled, and sent back to the absorber afterward. Working the absorber at high weights seems to have no cost advantage. To achieve the desired purity, the free gas output from the regenerator it is necessary to separate water in a separator tank. Then, the gases free from water are mixed with flue gases from CRU, then the mixed gases are compressed into liquid phases. The flue gas from the CRU does not require purification as it already contains more than 99% CO2. The pressure down in all equipment and the pipelines are regarded.

## Methodology for techno-economics

* 1. *Scope of CCS technology*

The scope of the study assumes plant capacity is 500,000 MT/year in 330 days/year and a lifetime of 20 years, which will stoichiometrically require 50 MT of natural gas per hour. The assumed operational in 330 days/years is standard practice for routine maintenance and unexpected downtimes in industrial operations. A typical ammonia production plant might not operate at full capacity every day due to scheduled maintenance activities, repairs, or equipment failures. The 330-day operational assumption allows for approximately 35 days of downtime per year, which is a reasonable estimate for many industrial facilities [9].

A 20-year lifetime allows for a reasonable period over which initial capital investments can be recovered through operational cash flows. This timeframe is often considered standard in many industrial sectors, including chemical manufacturing, to ensure that investors can recoup their investments while generating profit [10]. The systems and equipment are designed and sized based on HYSYS simulations. The equipment cost estimation methods are based on a Matche with CEPCI 2030, which is 320.29. The parameter for calculating techno-economic CCS technology is shown in Tab. 1. The prices calculated in this study are in US dollars in 2024.

**TABLE 1.** Parameter for techno-economic

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Value [$]** | **Reference** |
| Lifetime (years) | 20 | (Nosherwani & Neto, 2021) [1] |
| Electricity ($/kWh) | 0.064 | Pln.co.id, 2024 |
| MDEA solution ($/ton) | 1,250 | Alibaba.com, 2024 |
| Pipeline construction ($/mile) | 13,684.6 | (National Petroleum Council, 2021) [11] |
| Injecting cost ($/ton) | 10 | (National Petroleum Council, 2021) [11] |
| Capital investment grey ammonia ($/ton NH3) | 451.46 | (Oh *et al*., 2024) [12] |
| Manufacturing costs grey ammonia ($/ton NH3) | 155.52 | (Oh *et al*., 2024) [12] |

The first is to calculate the capital investment and operating cost of CCS technology. Capital investment consists of four components: Purchased Equipment Cost (PEC), Delivered Equipment Cost (DEC), Physical Plant Cost (PPC), and Direct Plant Cost (DPC). Then, Operating costs consist of Direct, Indirect, and Fixed Operating Costs.

* 1. *Levelized Cost of Ammonia (LCOA)*

The study aims to calculate LCOA after integrating CCS technology. According to the IEA, LCOA is a metric used to evaluate the overall cost of producing ammonia over its entire lifecycle. It provides a standardized way to compare the economic competitiveness of different ammonia production technologies, such traditional Haber-Bosch process, or blue ammonia with CCS technology.

The LCOA (*S*) is given by (Aries & Newton, 1955) [13].

*S = IFPk + M + G* (1)

*ra*

where *IF* is the fixed capital, *Pk* is ROI minimum or bank interest rate (10%), *M* is production cost per ton NH3, *G* is general expenses per ton NH3, *ra* is plant capacity per year.

* 1. *Sensitivity to capital cost*

Sensitivity analysis helps to determine the circumstances and conditions of any operating plant after investment. It is more useful when deciding on an investment. Sensitivity to capital cost can be determined by calculating the Internal Rate of Return (IRR). IRR is the most commonly used method to present the rate of economic return. The IRR value should be greater than the minimum attractive rate of return (MARR). It is the key tool to identify the plant’s total growth from start to end, and the degree of investment return at each stage of plant investment, IRR considers the value of money. For the successful operation of a pilot plant, it is essential to consider reasonable IRR, to avoid unnecessary risk throughout the life span of the plant. The IRR after and before tax is calculated based on the following eq [13].

𝑁

𝐼 = ∑

𝑗=1

𝐶𝑗/(1 + 𝐼𝑅𝑅)𝑗

(2)

where *I* is the capital investment, *C* is the net operating income, and *j* is the number of years.

* 1. *Payout time (POT)*

POT is the number of years in which the invested capital can be returned from the profit calculated before the depreciation is made. The POT after and before tax is calculated based on the following eq [13].

𝑃𝑂𝑇𝐴,𝐵

## Methodology for life cycle assessment (LCA)

* 1. *Goal and scope*

= 𝐹𝐶

(𝑃𝐴,𝐵×𝑟𝑎)+0,1𝐼𝐹

(3)

The study compares the potential environmental impacts of operating a grey and blue ammonia plant. With this approach, cradle-to-gate. Cradle-to-gate involves a comprehensive assessment of all stages, from the extraction of raw materials to the final production phase, to evaluate the environmental consequences of manufacturing a product. This study focused on the following stages: ammonia synthesis, CO2 synthesis, CO2 capturing using amine solvent, CO2 compression, pipeline transportation, and geological storage. The boundaries include CO2 emissions at the SMR and CRU. The process limitation is the use of CCS technology, and the functional unit in this study is 1 ton of ammonia. Fig. 2 is the boundaries system analysis.

Steam

Methanator

Ammonia

Converter

Refrigerator

CO2 Removal

Unit

Shift

Converter

Secondary

Reformer

Primary

Reformer

Feed Gas

Treatment

Natural Gas

Flue Gas

CO2

ECOSPHERE

Stack

Utility

Injecting

CCS PROCESS

Transporting

Capturing

CO2

TECHNOSPHERE

CO2

Air

Water Waste Water

Storage

**FIGURE 2.** Boundaries of system analysis LCA

* 1. *Life Cycle Inventory (LCI)*

This study uses quantitative secondary data to calculate emissions for the systems, using one year as the basis. Ammonia production in the Haber-Bosch process uses natural gas and steam at high temperatures and pressure. The value of CO2 generated in CCS utilization activities is estimated based on equation (4), a calculation established by the 2006 Intergovernmental Panel on Climate Change (IPCC). CO2 emissions from electricity use are estimated based on their emission factor value given by [14].

*EmissionsGHG,fuel= Fuel Consumptionfuel× Emissions FactorGHG, fuel* (4) where *emissionGHG,fuel* is emission of a given GHG by type of the fuel (kg GHG), *fuel consumptionfuel* amount of fuel combusted (TJ), and *emission factorGHG,fuel* default emission factor of given GHG by fuel type (kg gas/TJ).

* 1. *Life cycle impact assessment (LCIA)*

LCIA is a stage to determine the potential environmental impacts caused by the emissions generated. LCIA is carried out using the CML-IA baseline impact assessment method. Determination of environmental impact categories must be assessed including Global Warming Potential (GWP), ozone layer depletion, acidification potential, eutrophication potential, and cumulative energy demand.

The classification and characterization stage of each impact category is calculated and analyzed using OpenLCA 2.0.0 software and modelled based on the Ecoinvent (2010) V2.2. database.

# RESULT

## Simulation HYSYS

* 1. *Process simulation*

This study, uses acid gas chemical solvent as a fluid package. A fluid package for acid gas chemical solvents is a specific thermodynamic data set used to simulate the behavior of acid gases (such as CO2 and H2S) in specific chemical solutions. In the context of CO2 capture, these chemical solutions are typically amines (in this case, MDEA) that have a high affinity for CO2. The amines property bundle is selected as the acid gas chemical solvent due to its more reliable outputs compared to empirical models when used as the equilibrium model. 275,773.243 kg/h of flue gas combined from SMR and CRU at 37.27 bar pressure was treated in an amine-based absorption plant for carbon dioxide recuperation. The molar composition of the flue gases is shown in Tab. 2.

Fig. 1 shows the CO2 capturing plant for SMR and CRU gas cleaning. The simulation is done by Aspen HYSYS Version 11. Tab. 2 shows that the capturing plant's total efficiency is 99.6%, and the purity in the product stream is 96.1% CO2 with the total flow rate of CO2 product being 108,403.876 kg/h. Typical equipment used in simulation is

a mixer, separator, absorber, cooler, regenerator, reboiler, condenser, and compressor. For the amines, 56% MDEA was used, and the efficiency absorber was 99.87%.

* 1. *Phase of the product stream*

This study stream product is 35.04°C and 76.01 bars. CO2 products in a supercritical fluid phase are 34.99°C and

75.75 bars [15]. To allow for the most efficient injection conditions, the pressure and temperature of the CO2 in the pipeline will be maintained such that CO2 will be a supercritical liquid when it enters the injection well [16]. This CO2 product is ready to transport using pipelines 100 km with a pressure drop of 1.1 bars. Tab. 2. shows the results of components before and after treatment acid gas removal.

**TABLE 2.** Composition input and output

**Stream (mol/kg)**

**Component**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | |  | **Flue gas** | **CO2 Product** |
| CH4 | 0.000461 | 0.001138 |
| N2 | 0.520622 | 0.002925 |
| CO2 | 0.393590 | 0.970512 |
| CO | 7.25E-08 | 1.79E-07 |
| H2 | 0.000000 | 0.000000 |
| H2O | 0.072811 | 0.007751 |
| Ar | 0.012515 | 0.017674 |
| **2.** | **Techno-economic** |  |  |  |

Using the parameter values provided in the previous data, calculate CCS technology's capital investment and manufacturing costs, then add to grey ammonia’s capital investment and manufacturing costs to get blue ammonia results. The results of fixed capital and production costs of CCS technology are summarized in Tab. 3 and Tab. 4.

**TABLE 3.** Result of the fixed capital CCS  **TABLE 4.** Result of the production cost CCS

|  |  |
| --- | --- |
| **Component** | **Value [$]** |
| PEC | 38,260,741.89 |
| DEC | 6,040,414.63 |
| PPC | 91,663,172.38 |
| DPC | 109,995,806.86 |
| **Fixed Capital** | **214,574,131.80** |

|  |  |
| --- | --- |
| **Component** | **Value [$]** |
| Direct | 43,702,715.45 |
| Indirect | 21,120.00 |
| Fixed | 27,894,637.13 |
| **Production Costs** | **71,618,471.59** |

Tab. 5 shows if integrating CCS technology in the ammonia plant increases capital investment and production cost. But also increases the price of ammonia. The LCOA shows a similar pattern. Grey ammonia has LCOA at $196.28/ton, followed by blue ammonia at $378.74/ton, which is 45% higher. These results are consistently stated by the International Renewable Energy Agency (IRENA) and Ammonia Energy Agency (AEA) (2022), where LCOA ranges from $110/ton to $340/ton for grey ammonia and $360/ton to $450/ton for blue ammonia [17].

Other studies from Tjahjono et al., 2023 investigated and calculated the feasibility of gray, blue, and green ammonia productions in Indonesia, and the results are LCOA for blue ammonia is approximately $390/ton NH3, making it a more stable option than gray ammonia, which costs about $297/ton NH3. The latter is significantly influenced by fluctuating natural gas prices and carbon taxation. The costs associated with CCS are significant for blue ammonia production, accounting for approximately 28% of its total LCOA. This includes costs for capturing CO2 at around $70 per ton and storage expenses of about $10 per ton.

**TABLE 5.** Result comparison of grey and blue ammonia

|  |  |  |
| --- | --- | --- |
| **Component** | **Grey Ammonia** | **Blue Ammonia** |
| Capital Investment ($) | 225,730,485.39 | 461,762,030.37 |
| Production Cost ($/year) | 77,758,444.83 | 149,376,917.42 |
| General Expenses ($) | 20,379,642.41 | 39,993,821.46 |
| Price ($/ton NH3) | 245.94 | 378.74 |
| Total sales per year ($/year) | 122,968,440.63 | 189,370,738.88 |
| IRR Before Taxes (ROI-b) | 24.57% | 24.05% |
| POT Before Taxes (POT-b) | 10 | 10 |

The LCOA values obtained from this study are in reasonable agreement with the industry estimates. For the low-risk chemical industry, the minimum acceptable IRR before tax is 11%, and for the POT is 5 years [13]. The IRR blue ammonia in this study is 24.05% and the POT is 10, hence integrating CCS technology in the ammonia plant is worth establishing because the IRR and POT are higher than the minimum acceptable IRR and POT.

## 3. Life Cycle Assessment

Fig. 3 shows the results for the considered impact categories in grey and blue ammonia, while Fig. 4 shows the results of the energy use in the production of grey and blue ammonia.

- Global Warming Potential (GWP)

Global warming is an increase temperature on the earth's surface caused by the trapping of heat or solar radiation by GHG and cannot be released into the atmosphere. GHG gasses include carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O). Based on the analysis, the potential cause of GHG impacts is dominated by fossil CO2 resulting from the use of natural gas combustion as an energy source.

The results of GWP on the comparison of grey and blue ammonia processes, show that blue ammonia has a significant decrease in GWP environmental impact. Blue ammonia produces 787.1 kg CO2 eq ton NH -1 or about

3

2.5 times lower than grey ammonia (2004.4 kg CO2 eq ton NH -1).

3

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  | | |
|  |  | | |
|  | 787.1147 | | |
|  |  |  |  |

a. b.

Climate Change

2400

2000

1600

1200

800

400

2004.3626

Grey Ammonia

Blue Ammonia

Eutrophication Potential

1200.0000

1000.0000

800.0000

600.0000

400.0000

200.0000

955.6925

953.5730

Grey Ammonia Blue Ammonia

Acidification Potential

6.0000

5.0000 4.6015 4.8250

4.0000

3.0000

2.0000

1.0000

0.0000

Grey Ammonia Blue Ammonia

Ozone Layer Depletion

0.000375 0.00036

0.00035 0.00033

0.000325

0.0003

0.000275

0.00025

0.000225

0.0002

Grey Ammonia Blue Ammonia

Kg CO2 eq

Kg SO2 eq

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
|  |  |
|  |  |
|  |  |
|  |  |

* 1. d.

Kg PO4 eq

Kg CFC-11 eq

**FIGURE 3.** Environmental impacts of the grey and blue ammonia: a. global warming potential (GWP), b. acidification

potential (AP), c. eutrophication potential (EP), and d. ozone layer depletion. The impact of grey and blue ammonia production is mentioned in each graph

**FIGURE 4.** Energy use in the production of grey and blue ammonia

Cumulative Energy Demand

5.70E+04

5.40E+04

5.40034E+04

5.10E+04 4.87064E+04

4.80E+04

4.50E+04

4.20E+04

3.90E+04

3.60E+04

3.30E+04

Grey Ammonia Blue Ammonia

MJ

* Acidification Potential

Acidification is the process of acidic gases such as sulfur dioxide (SO2) reacting with water in the atmosphere to form acid rain. The gases that cause acidification are ammonia (NH3), nitrogen oxides (NOx), and sulfur dioxide (SOx). These gases form by the combustion of fossil fuels.

The results of the calculation of the environmental impact of acidification in the comparison of the grey and blue ammonia processes show that blue ammonia has an increase in potential impact but is not significant. The contributor to the impact of acidification is the use of natural gas as energy, and this is linear with the increasing amount of natural gas demand in the blue ammonia process.

* Eutrophication

Eutrophication is an impact on aquatic ecosystems that is influenced by macronutrient materials in the form of nitrogen, phosphate, and chemical oxygen demand (COD) parameters. Based on the impact analysis, the largest contribution is dominated by nitrogen released to the environment from the CO2 capturing process.

The results of the calculation of the environmental impact of eutrophication on the comparison of the grey and blue ammonia processes, show that blue ammonia has decreased in impact but not significantly. This happens because one of the contributors is nitrogen in flue gas, in the grey ammonia production is a release of nitrogen gas into the environment. However, the production process of blue ammonia releases less nitrogen gas.

* Ozone depletion

Ozone depletion is the reduction of ozone levels in the stratosphere layer due to the formation of reactive chemicals due to reactions with sunlight with pollutants such as CH4, NOx, carbon monoxide (CO), and SO2. Burning of fossil fuels is a factor in the formation of these gases.

The results of the calculation of environmental impacts show that blue ammonia does not have a significant impact, the impact is already low.

* Cumulative energy demand

Cumulative energy demand is the amount of energy required in one life cycle to produce a product both directly and indirectly. This assessment of energy use refers to the non-renewable fossil category. From the results, there has been an increase in energy demand in the blue ammonia manufacturing process by 10.88%.

The interesting result is while GWP decreases, the LCA results indicate that certain processes involved in blue ammonia production can lead to an increase in acidification potential. This is primarily due to emissions of SO2, NOx, and NH3 which contribute to acid rain formation. The production of blue ammonia involves the reforming of natural gas, which while capturing a significant portion of CO2 emissions, still releases other pollutants that can lead to acidification. The carbon capture technologies used may not fully mitigate all associated emissions, particularly those related to NOx.

# CONCLUSION

This study demonstrates the feasibility of integrating CCS technology into existing ammonia plants to produce blue ammonia, a crucial step towards decarbonizing the Industrial Park and Petrochemical Units (IPPU) sector. Simulation results using Aspen HYSYS show promising CO2 capture efficiency of 99.6% from flue gases.

However, the techno-economic analysis reveals a 105% increase in CAPEX and a 48% increase in OPEX for blue ammonia production compared to grey ammonia, primarily due to the added investment for CCS.

LCA results confirm the significant environmental benefits of blue ammonia, with a GWP of 0.787 kg CO2- eq/kg NH3 compared to 2 kg CO2-eq/kg NH3 for grey ammonia. While blue ammonia demonstrates a substantial reduction in GWP, it also exhibits increased impacts in certain categories, such as energy consumption and resource depletion, primarily attributed to the higher energy demand for CCS operations.

To enhance the competitiveness of blue ammonia production, the implementation of robust policy incentives is crucial. Mechanisms such as carbon pricing, tax breaks for CCS investments, and subsidies for low-carbon technologies can significantly incentivize adoption. Furthermore, exploring the integration of renewable energy sources with CCS technologies, such as utilizing solar or wind power to offset the energy demand of the CCS process, presents a promising avenue for further decarbonization.

Moving forward, a comprehensive cradle-to-grave LCA, considering the entire life cycle of blue ammonia production and its subsequent utilization, is recommended to provide a more holistic understanding of its environmental impacts.

While blue ammonia offers a viable pathway towards decarbonization in the IPPU sector, it is crucial to acknowledge the challenges. High initial investment costs, the need for robust infrastructure for CO2 transportation and storage, and the requirement for long-term regulatory support to ensure environmental integrity and public acceptance are critical considerations for successful implementation.

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