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Regional Case Study

Environmental Performance of Ammonia Production in Indonesia using Life Cycle Assessment Approach (A Sensitivity Analysis of CCUS Implementation)

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Abstract

Ammonia is a fundamental component in fertilizer and chemical manufacturing processes around the world, but its production is a significant contributor to CO_2 emissions in chemical industry. Implementation of carbon capture utilization and storage (CCUS) offers an alternative decarbonisation strategy to mitigate CO_2 emissions in ammonia production. This study assesses the environmental performance of ammonia production through life cycle assessment (LCA) methodology. Environmental impacts are calculated using openLCA software with various impact assessment methods, including CML-IA Baseline, Impact 2002+, Recipe 2016 Midpoint (H), and AWARE. The study scope encompasses the cradle-to-grave analysis, from the extraction of raw materials and transportation to ammonia production, main processes, distribution, and consumer product consumption, with a declared unit of 1-kg ammonia product. Our findings showed that CO_2 removal and Power Plant in core processes in the core process as the most significant contributors to Global Warming Potential. Therefore, sensitivity analysis was conducted by reducing CO_2 emission by 10% and 70% through CCUS implementation. The results showed that the CCUS implementation could reduce Global Warming Potential by up to 43%.

Keywords: Ammonia production; carbon capture utilization and storage; environmental performance; life cycle assessment; sensitivity analysis

1. Introduction

Ammonia (NH_3) is an inorganic substance formed out of nitrogen and hydrogen, derived from the processing of natural gas. It is a colourless and pungent-smelling gas at room temperature. As highlighted by Liu et al. (2020), it holds the position of the second most produced chemical globally and plays a crucial role as a fundamental component in the manufacturing processes of fertilizers and various other chemical products. Over 75% of the ammonia produced is consumed by the agricultural sector specifically as a fertilizer, as emphasized by Erdemir & Dincer (2021) . This chemical compound, ranks second after sulfuric acid (H_2SO_4), as stated by Ghavam et al. (2021). The International Renewable Energy Agency (IRENA) reported that the global supply capacity of ammonia was 183 million tons in 2019 and is expected to increase to 688 million tons by 2030 (IRENA nad AEA, 2022). In 2018, the worldwide output of ammonia reached 140 million tons, while China contributed 31.4%, subsequent by Russia 10%, the US 8.9%, and India 7.8% (Zhang et al., 2022).

In 2015, the production of ammonia reached about 1.5 × 108 tonnes, primarily sourced from natural gas (72%), coal (22%), oil (4%), and other feedstocks (Khasani et al., 2021). As the world's largest ammonia producer, China accounts for nearly 32% of global production, utilizing a diverse mix of feedstocks: 70% coal, 10% oil products, and only 20% natural gas. The Haber-Bosch process has revolutionized ammonia production, by harnessing atmospheric nitrogen and extracting hydrogen from water or by the catalytic steam reforming of natural gas. This process relies on fossil fuels for hydrogen production as both a feedstock and fuel source (van Langevelde et al., 2021). Hydrogen is generated in ammonia plants through the use of steam-methane reforming (SMR) and water-gas shift (WGS) processes. Subsequently, the hydrogen is purified to be used in the high-pressure ammonia synthesis. The process of synthesis involves the combination of hydrogen and nitrogen in a ratio of 3:1 by moles, followed by compression at high pressure (up to 200 bar) and temperature (up to 400 ^{o}C). The production of synthetic ammonia using catalytic steam reforming involves six essential process processes. The processes involved in natural gas treatment include desulfurization, catalytic steam reforming, carbon monoxide shift, carbon dioxide removal, methanation, and ammonia synthesis. Of these, the removal of pollutants from natural gas, such as sulphur, CO, CO2, and water, requires four essential procedures (Luis, 2016)

Despite its significance in various industries, evidence suggests that ammonia production stands out as a major contributor to CO2 emissions within the chemical sector. The manufacture of ammonia alone accounts for around 2% of global fossil energy consumption, resulting in the emission of over 420 million tonnes of CO2 per year. This represents 1.2% of the total anthropogenic CO2 emissions worldwide (Liu et al., 2020). According to MacFarlane et al. (2020), ammonia manufacturing presently contributes to approximately 1% of worldwide greenhouse gas emissions or nearly 1.4% of global CO2 emissions. The average emissions from ammonia production globally are approximately 2.9 tonnes of CO2 per tonne of NH3. Furthermore, the International Renewable Energy Agency (IRENA) states that the ammonia production business provides 0.5 gigatonnes (Gt) of carbon dioxide (CO2) emissions each year. This accounts for approximately 1% of worldwide CO2 emissions and 15-20% of the chemical sector's CO2 emissions (IRENA and AEA, 2022).

The ammonia plant is designed to have two main sources of CO2 emissions, come from the reformer unit and the stripper unit (Morales Mora et al., 2016). Furthermore, the Haber-Bosch process exhibits disadvantages such as substantial greenhouse gas emissions that surpass 2.16 kgCO2-eq/kg NH3 and considerable energy consumption of more than 30 GJ/tonne NH3. The strict operational requirements of high temperature and pressure mostly cause these drawbacks (Ghavam et al., 2021a). Reviewing the literature underscores CO2 as a significant contributor to emissions in the ammonia production process. Addressing the impact of climate change and emissions from ammonia production necessitates effective CO2 management through life cycle thinking and sustainable concepts. This strategy has resulted in the creation of cutting-edge technologies that aim to make use of waste resources, promote effective management of resources and space, and facilitate the practical utilisation of waste streams such as food, human waste, and CO2 (Ghavam et al., 2021b).

One alternative decarbonisation strategy for managing CO2 is the implementation of Carbon Capture Utilization and Storage (CCUS) in ammonia production. According to Chen et al. (2022), CCUS technology is crucial for reducing greenhouse gas emissions and achieving worldwide carbon neutrality. This prospective decarbonization technology involves capturing CO2 from exhaust gas or the atmosphere and then transporting it for permanent use or storage. Zhang et al. (2022) also stated that CCUS refers to capturing and separating CO2 from various sources and transporting it for utilization or geologic sequestration, ultimately reducing CO2 emissions. Carbon dioxide utilization and burial, transport, and capture are the three primary components of CCUS, each with its technical framework and theoretical foundation. It signifies a shift from simply sequestering carbon dioxide to purifying and incorporating it into new production processes for recycling (Cao et al., 2022). CCUS is widely acknowledged for its crucial role in various mitigation scenarios. For instance, the International Energy Agency (IEA) reports CCUS has the potential to provide a 15% contribution to the Sustainable Development Scenario (SDS) by the year 2070 (EIA, 2020). China, being the foremost emitter of carbon dioxide globally, has set a goal to attain carbon neutrality by 2060 by employing CCUS technologies. CCUS is projected to decrease emissions by around 600–1400 Mt CO_2 and 1000–1800 Mt CO_2 in 2050 and 2060, respectively (Chen et al., 2022). Wang et al. (2023) found that by 2040, if the reduction of carbon emissions using CCUS increases by 30%, it is projected that CCUS could eliminate 3.8% of carbon emissions in China. The chemical industry stands to benefit significantly, with CCUS contributing to a notable 17.31% reduction in emissions. These findings underscore the potential of CCUS in emissions reduction strategies within the chemical industry.

The Life Cycle Assessment (LCA) was utilized to undertake a comprehensive review of the environmental effects associated with implementing or not implementing CCUS in ammonia production, supporting decision-making for sustainable growth. By evaluating and quantifying all inputs and outputs, their environmental results can be comprehensively assessed to determine which path or process has the greatest impact on the environment.

Many valuable studies have been conducted on the LCA of ammonia production. Arora et al. (2018) quantified the emission of carbon and expenses associated with ammonia production, using 1 kg of ammonia as the declared unit. Their research quantified the greenhouse gas emissions associated with activities such as coal mining, biomass harvesting, transportation, electricity generation, and utilities. Additionally, they performed an LCA specifically focused on ammonia manufacturing. The LCA findings indicate that coal gasification has the highest Global Warming Potential (GWP) with a value of 4.22 kg CO_2eq/kg NH_3, followed by biomass gasification with 1.2 kg CO_2eq/kg NH_3. The GWP of steam methane reforming (SMR) of natural gas is 2.81 kg CO_2eq/kg NH_3 and biomass gasification at 1.2 CO_2eq/kg NH_3. The GWP for natural gas, biomass, and coal from ammonia production without the Carbon Capture and Storage (CCS) process was determined to be 2.81, 1.2, and 4.2 kg CO_2eq/kg NH_3, respectively. Makhlouf et al. (2015) performed an LCA and provided the impact findings for the production of 1 tonne of ammonia using SMR of natural gas in Algeria. The findings indicated that the GWP is elevated, mostly due to the significant quantity of greenhouse gas (GHG) emissions, specifically 1.44 t CO_2eq/t of NH_3, albeit this value is lower than the global average. According to LCA studies by Parkinson et al. (2018), in the process of SMR combined with Haber-Bosch, 0.66 metric tons of water (H_2O) is used to produce 1 metric ton of ammonia. Additionally, over the whole life cycle of this process, around 9-10 t CO_2eq is generated.

Meanwhile, the study by Boero et al. (2021) evaluates the implementation of CCUS and without CCUS. Adding carbon capture techniques to steam reforming enhances performance by reducing carbon emissions, resulting in an almost 60% decrease in GHG emissions with the addition of CCS. Additionally, other effect categories saw increases: FEP rose by 56%, IRP by 47%, and the remaining categories by less than 8%. The increased energy required to operate the CCS system. A sensitivity analysis was carried out for 20 years, revealing that the Global Warming Potential over a 100-year period (GWP100) for the installation of CCS by SMR is 1.12 t CO_2/t NH_3, while SMR without CCS is 2.75 t CO_2/t NH_3. Implementing CCS leads to a 44% decrease in the carbon footprint of 1 ton of ammonia produced through SMR. This reduction is lower compared to what was previously forecasted for GWP100.

Therefore, it is essential to assess the ammonia industry's impact in Indonesia from a life cycle perspective in order to ensure clean, efficient, and sustainable development in the sector. There have been several LCA studies on ammonia production, but of all these studies, none has specifically discussed sensitivity analysis scenarios to see the potential for reducing impacts due to CCUS implementation. With the use of open LCA software and the LCA approach, this study attempts to close the gap between the environmental impacts with and without CCUS and analysing the potential implementation of CCUS using the LCA method.

2. Methods

2.1 Life Cycle Assessment (LCA) Methodology

Life Cycle Assessment (LCA) involves creating a comprehensive breakdown of the energy and materials used at each stage of the product's life cycle, and then calculating the related resource consumption and emissions (Liu et al., 2020). LCA is the first step to improving the environmental performance of ammonia production companies, providing a foundational framework for developing policies that can guide decision-makers in the industry, government, or non-governmental sectors. The LCA study in this paper adheres to established standards ISO 14040, ISO 14044, and Product Category Rules (PCR) 2021:03 Basic Chemicals UN CPC 341, 342, 343, 345 (Except Subclass 3451) Version 1.0 of 2021. The four phases of LCA for ammonia production based on the ISO standards are goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation.

2.1.1. Goal and Scope

The goal and scope are crucial components, including objectives, system boundary, and functional/declared unit. The goal of this LCA study is to identify lifecycle stages causing the most significant environmental impacts (hotspots) while pinpointing opportunities for enhancing environmental performance and reducing overall environmental impacts. The study covers all stages from raw material extraction to ammonia production. The system boundary is cradle-to-grave, divided into three parts: upstream processes, core processes, and downstream processes. This includes raw material extraction, main product production, utility processes supporting production, waste processing after production, product distribution, and consumer product consumption. The system boundary is shown in Figure 1. The declaration unit for this study is 1 kilogram of the product, representing 100% of the total unpackaged liquid ammonia produced, distributed, and consumed by the ammonia plant. This declaration unit aligns with the Product Category Rules (PCR) 2021:03 Basic Chemicals UN CPC 341, 342, 343, 345 (Except Subclass 3451) Version 1.0 Year 2021. Assumptions made in this study include:

- Downstream processes encompass the distribution of unpackaged liquid ammonia products to consumers and the consumption of liquid ammonia by consumers.
- Transportation, involving trucks for diesel fuel transport and some chemical products, is assumed to use a 3.5-7.5 metric ton Euro 3 truck in the Ecoinvent v.3.8 database for the year 2022.
- The distance for ammonia product delivery is calculated using the distance approach on Google Maps.

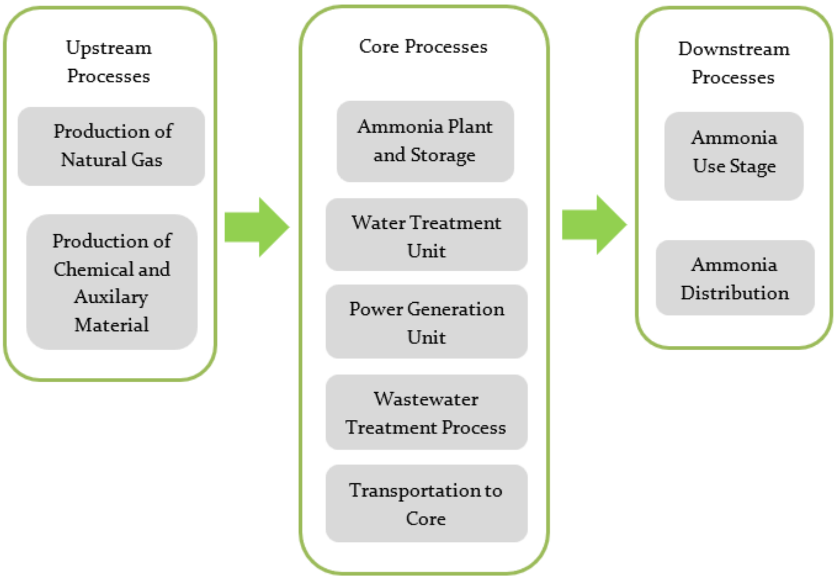

Figure 1. System boundary of ammonia production

2.1.2. Life Cycle Inventory (LCI)

This phase involves gathering necessary data for achieving the defined study's objectives. Data related to every process unit within the designated system boundary, can be categorized into major headings, encompassing energy input, raw material inputs, additional inputs, products, co-products, and waste and emissions (to air, soil, and water) (Mahmud et al., 2020). Two types of data sources are utilized: primary data, derived from actual industry measurements and calculations during the ammonia production period from 2020 to 2021, and secondary data derived from the Ecoinvent 3.8 database, journals, and literature studies.

2.1.3. Life Cycle Impact Assessment (LCIA)

The LCIA involves evaluating the significant environmental impact potential by utilizing the results from the life cycle inventory analysis. The selection of impact categories assessed, and the methodology used depend on the goals and scope of the research. This study calculated several environmental impact categories, especially global warming potential, abiotic depletion potential (fossil fuels), human toxicity, acidification, carcinogenic, land use change, and water scarcity footprint. This calculation was performed using the CML-IA, Recipe (H) 2016, Impact 2002+, and AWARE Life Cycle Impact Assessment (LCIA) methods through openLCA v.2.0 software. openLCA is software that assists in analysing the stages of an LCA study. It offers several features, including flows, which represent the input and output of all products, materials, or energy in each production process. The database contains secondary data relevant to the production process, such as energy, materials, and emission flows from components. Processes within openLCA are the functionalities provided to convert inputs into outputs. Each process is defined by its output flow, serving as a quantitative reference for product flows utilized in a project. According to Mehmeti & Canaj (2022), the CML method, known for its versatility in assessing a broad range of environmental impacts, has been utilized in the Middle East, Asia, and Europe. Meanwhile, Nguyen et al. (2020) stated that the ReCiPe method, primarily applied in a European context due to its capability to provide global characterization factors, offering indicators applicable at both national and international levels. With 18 midpoint environmental impact categories, ReCiPe offers a comprehensive perspective compared to the 10 categories in CML, making it suitable for global-scale applications. Additionally, the AWARE (Available Water Remaining) method, as a consensus-based approach, specifically addresses water scarcity footprint assessments in LCA (Mehmeti & Canaj, 2022).

2.1.4. Interpretation Phase

During this phase, the significant issues found in the results of the LCI and the LCIA are discussed. This analysis is used to draw conclusions, offer suggestions, and make decisions that align with the aim and scope of this work.

2.2 Sensitivity Analysis

Sensitivity analysis is a step of examining or testing the effect of assumptions and methods on the results of impact assessment. The procedure for sensitivity analysis involves comparing outcomes obtained using particular assumptions designed to enhance environmental performance in certain impact categories. Shirmohammadi et al. (2020) applied sensitivity analysis in their research to assess crucial factors such as heat consumption, efficiency of capturing, and operational capability of the simulated plant. Similarly, Monteiro & Roussanaly (2022) utilized sensitivity analysis to comprehend the influence of costs on CCUS avoidance costs and to draw relevant conclusions. In the present study, sensitivity analysis was used to define the effects of carbon capture potential on LCIA. The analysis involved varying the CO_2 output parameters with reductions of 10% and 70%, simulating the application of CCUS technology on the plant. According to G. Liu et al. (2022) full implementation of CCUS can reduce total CO_2 emissions by 5-10%. Additionally, Singh & Colosi (2021) stated that typical CO_2 capture rates for fossil supply chains with CCS range from 70% to 95%, indicating that while some CO2 is sequestered, there are still emissions present. of CCUS using the LCA method.

3. Result and Discussion

3.1 Life Cycle Assessment (LCA) Modelling

The initial phase involves gathering detailed information about the product system under scrutiny. This includes data on material inputs, energy consumption, and waste outputs throughout the product's life cycle, Table 1 shows the upstream process, Table 2 displays the core process, and downstream process (can be seen in Table 3). The graphical representation is designed to enhance clarity and facilitate a better understanding of the complex interrelationships between the various stages of the product lifecycle. Once the flow diagram is finalized, the information is then transposed into openLCA to create the necessary flow and product systems. Subsequently, flows are modelled and categorised according to each unit process. The input-output values of each material flow are based on inventory data. This is followed by creating a product system that visually represents the overall direction of the ammonia production process. The final step is the calculation of the ammonia production process model, leading to an analysis of the product's environmental footprint, aiding in identifying areas that require further attention or improvement for a more sustainable outcome.

Table 1. Summary of upstream process inventory (per declared unit)

Category Inputs	Inventory Data	Amount	Unit
Production	Fuel	4.75E-04	kg
	Sulfuric acid	2.68E-04	kg
	Natural gas	3.56E-05	MMSCF
	Sodium Hydroxide	3.53E-04	kg

Table 2. Summary of core process inventory (per declared unit)

Category Inputs	Inventory Data	Amount	Unit
Raw Materials	Natural gas	2.94E-05	MMSCF
Supporting Materials	Sea water	9.35E+01	kg
	Air	2.65E+00	kg
Energy	Fuel	4.74E-04	kg
	Natural gas	4.70E-02	kg
	Electricity	1.41E+02	kg
	Steam	1.11E+01	kg
Chemicals	Sodium Hydroxide	3.53E-04	kg
	Sulfuric acid	2.68E-04	kg
Category Outputs	**Inventory Data**	**Amount**	**Unit**
Product	Ammonia	1.00E+00	kg
Hazardous waste	Hazardous waste	5.04E-04	kg
Non-hazardous waste	Non-hazardous waste	6.13E-04	kg
Emissions to water	Oils and Fats	1.78E-06	kg
	COD	1.14E-05	kg
	Ammonia	1.69E-05	kg
Emissions to air	CO2	1.68E+00	kg
	CO	8.87E-01	kg
	Nitrogen oxide	5.16E-04	kg
	Sulfur oxide	5.77E-04	kg
	Sulfur dioxide	4.33E-06	kg
	Particulate	6.54E-05	kg
	Oxygen	3.88E-05	kg

Table 3. Summary of downstream inventory (per declared unit)

Category Inputs	Inventory Data	Amount	Unit
Transportation	Distribution of ammonia to customers	1*2.22E+04	kg*km

3.2 LCA Result for Ammonia Plant

The entire ammonia production process begins with upstream processes, comprising natural gas production, sodium hydroxide production, diesel production, and biodiesel production (fatty acid methyl ester). It continues to the core processes, including CO2 removal, natural gas transport, power plant, boiler, and primary reformer, and concludes with downstream processes involving ammonia distribution. The environmental performance results of ammonia production can be seen in Table 4 and Figure 2.

Table 4. Environmental impact of ammonia production (per declared unit)

Calculation Method	Impact Category	Upstream	Core	Downstream	Total Impact	Reference Unit
CML-IA Baseline	Global Warming potential (GWP)	2.70E-01	1.68E+00	1.66E-01	2.12E+00	$kgCO_2eq$
	Abiotic depletion potential (fossil fuel)	3.68E+01	4.45E-02	2.12E+00	3.90E+01	MJ
	Human Toxicity Potential (HTP)	3.09E-01	1.24E-03	6.92E-02	3.79E-01	kg 1,4-DB eq
	Acidification Potential (AP)	1.72E-03	2.72E-04	3.99E-03	5.98E-03	$kgSO_2eq$
Impact 2002+	Carcinogenic Potential	4.24E-01	1.81E-04	1.18E-03	4.26E-01	kgC_2H_3Cleq
ReCiPe 2016 Midpoint (H)	Land use	1.72E-03	1.67E-05	9.46E-04	2.68E-03	m^2a
AWARE	Water use	1.37E-02	2.83E-04	5.73E-03	1.97E-02	m^3

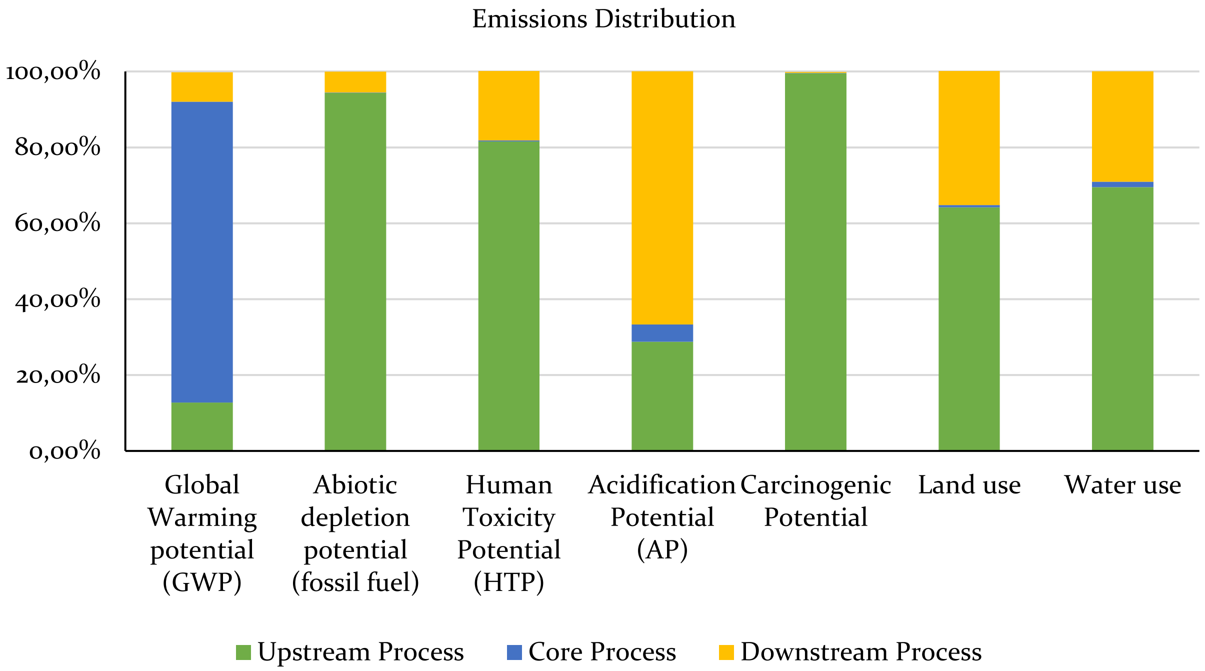

Figure 2. Emissions distribution in the cradle-to-grave scope

Based on the LCA analysis, the upstream process shows significant impacts on several impact categories, including Abiotic Depletion Potential (fossil fuel) at 94.45%, Human Toxicity Potential (HTP) at 81.41%, Carcinogenic Potential at 99.68%, Land use at 64.08%, and Water scarcity footprint at 69.45%. Natural gas production is the primary contributor, involving extraction, transportation, and purification processes with high energy consumption, water usage, and forest land changes. The process results in toxic emissions such as benzene and barium into water and dioxin emissions into the air, which pose potential health risks to humans. These findings align with Muhamad et al. (2022), which highlights that extraction and combustion of fossil fuel resources, particularly natural gas, contribute to Abiotic Depletion Potential (fossil fuel) and Human Toxicity Potential (HTP), with compressor units playing a significant role. According to Cavalcanti et al. (2021), the major impact categories correlated to gas production include fossil fuel extraction (accounting for 40.2% of the impacts during primary processing), inorganic respiratory effects (35.6%), climate change (14.5%), and acidification/eutrophication (6.6%). Furthermore, 26.5% of the gas produced is allocated for generating electricity and heat after being consumed during purification and transmission. The purifying process necessitates substantial heat and energy, generated by gas combustion.

The core process significantly impacts the Global Warming Potential (GWP) category at 79.44%. The CO2 removal unit within the core process emerges as the primary contributor to GWP impact, followed by power plant units. This is attributed to the high carbon dioxide emissions generated during the CO2 removal process, aimed at purifying natural gas from carbon dioxide impurities to enhance ammonia production efficiency. These findings align with Morales Mora et al's study. (2016), where 99.4% of the 297.5kgCO2e/bbl GWP impact in the ammonia production process was cause by the CO2 removal unit and shift, accounting for 50.8% of the total impact. On the other hand, the downstream process significantly impacts the Acidification Potential (AP) category at 66.64%, with ammonia distribution emerging as the primary contributor. This is attributed to the reliance on fossil-derived fuels in this process, resulting in emissions such as nitrogen oxides and sulfur dioxide. These gases have the ability to mix with water vapour to produce nitric and sulfuric acids, which can then fall as acid rain on the earth. Hannun & Abdul Razzaq (2022), stated the pollutants generated from burning fossil fuels (oil, gas, and coal), including sulfur dioxide, carbon dioxide, nitrogen oxides, and particulates. It is widely known that sulphur dioxide and nitrogen oxides both contribute to the creation of acid rain when they react with water.

3.3 Sensitivity Analysis

Based on the LCA results, the core process is identified as the hotspot in the GWP impact category due to having the highest GWP value compared to other processes. The unit processes within the core process that significantly contribute to CO2 emissions are CO2 Removal and the Power Plant. Therefore, this study conducts a sensitivity analysis by examining the environmental impact reduction through the implementation of CCUS. The analysis focuses on varying the CO2 output parameters within the unit processes of CO2 removal and Power Plant, with reductions of 10% (Scenario 1) and 70% (Scenario 2) as CCUS implementation assumptions, as presented in Table 5. After the adjustments in CO2 output parameters, the environmental impact analysis is recalculated by modifying the CO2 output parameter values using openLCA, yielding the environmental performance results as presented in Table 6.

Table 5. Scenario variations of CO2 emission value

Unit Process	CO_2 Basis	Unit	Scenario 1	Scenario 2
CO_2 Removal	6.98E+05	Ton	6.28E+05	2.09E+05
Power Plant	4.19E+04		3.77E+0	1.25E+04

Table 6. Environmental performance results of various scenarios of CCUS implementation

	Impact category	Reference unit	Environmental Impact Score			Percent Impact Reduction	
			Basis	Scenario 1	Scenario 2	Scenario 1	Scenario 2
1	Abiotic depletion (fossil fuels)	MJ	3.88E+01	3.88E+01	3.88E+01	0.00%	0.00%
2	Global warming (GWP100a)	kg CO_2-eq	2.11E+00	1.98E+00	1.19E+00	5.79%	43.33%
3	Human toxicity	kg 1,4-DB eq	3.77E-01	3.77E-01	3.77E-01	0.00%	0.00%
4	Acidification	kg SO_2-eq	5.97E-03	5.97E-03	5.97E-03	0.00%	0.00%
5	Land use	m^2a	1.83E-03	1.83E-03	1.83E-03	0.00%	0.00%
6	Water use	m^3	1.95E-02	1.95E-02	1.95E-02	0.00%	0.00%
7	Carcinogenic potential	kg C_2H_3Cl-eq	4.24E-01	4.24E-01	4.24E-01	0.00%	0.00%

Based on Table 6, it can be observed that the implementation of CCUS in ammonia production has an effect on the GWP (Global Warming Potential) scores, but it does not affect other impact categories. There is a significant decrease in the GWP impact, amounting to 5.79 % for scenario 1 and 43.33% for scenario 2. This reduction is attributed to the decrease in CO2 values, which directly influences the GWP impact. The smaller the CO2 output values in a production process, the smaller the GWP impact of that production process. The GWP impact is a metric used to measure the amount of CO2 emissions produced during the entire life cycle of a product.

Kerr et al. (2022) stated that lower GWP could be achieved by reducing the product carbon emissions. Facchino et al. (2022)have reported that the storage of captured CO2 has been found to significantly reduce the Global Warming Potential (GWP) by up to 89% in Italy and up to 97% in Poland. In contrast, when CO2 is partially used to make dimethyl ether, there is a reduction of up to 58% in Italy and up to 68% in Poland. CCUS technologies have the potential to reduce carbon emissions from ammonia manufacturing, with expectations of up to a 90% reduction in carbon emissions (Raksajati et al., 2013). Ammonia produced by combining traditional production with CCU or CCUS is referred to as blue ammonia. Green ammonia production is a process that involves creating ammonia solely from renewable energy sources. This process results in nearly carbon-neutral production. Blue and green ammonia are both used as clean fuel substitutes for fossil fuels, and play an important role in reducing carbon emissions within the power and transport industries(Tjahjono et al., 2023).

4. Conclusions

The LCA method was utilized in this study to assess the environmental impact and potential improvement of ammonia production with the potential incorporation of CCUS. The LCA results indicate that ammonia production affects various impact categories, with the upstream process significantly impacting several categories, including Abiotic Depletion Potential (fossil fuel) at 94.45%, Human Toxicity Potential (HTP) at 81.41%, Carcinogenic Potential at 99.68%, Land use at 64.08%, and Water scarcity footprint at 69.45%, where natural gas production is the primary contributor. Additionally, the core process significantly affects the GWP category at 79.44%, with the CO_2 removal unit being the main contributor, while the downstream process significantly affects the Acidification Potential (AP) category at 66.64%, with ammonia distribution being the main contributor. Based on these LCA findings, the core process is identified as the hotspot for the GWP impact category, thus a sensitivity analysis is required to assess CCUS implementation's environmental impact reduction. The analysis reveals a significant decrease in GWP impact, reaching 5.79% for scenario 1 (a 10% reduction in initial CO_2 value) and 43.33% for scenario 2 (a 70% reduction in initial CO_2 value). This study only examines a few limited impact categories. Future research endeavours could undertake an in-depth analysis of other impacts and scope of category from CCUS system that may have significant influence and address the social, economic, and environmental aspects to implement CCUS in ammonia production effectively.

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