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Research Article

# Assessing the feasibility of gray, blue, and green ammonia productions in Indonesia: A techno-economic and environmental perspective

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**Abstract**. Ammonia, owing to its carbon-free attributes, stands as a promising alternative for replacing fossil-based fuels. This study investigates the techno-economic and environmental aspects of gray, blue, and green ammonia production in Indonesia. In this regard, a spreadsheet-based decision support system has been developed to analyze the levelized cost of each mode of ammonia production and their cost sensitivity across various parameters. The results of the analysis show a levelized cost of gray ammonia of $297 (USD) per ton, which is strongly affected by natural gas prices and carbon taxation. Blue ammonia emerges as the most stable production option with a levelized cost of $390 per ton, impacted by natural gas prices and the expenses associated with carbon sequestration. On the other hand, the levelized cost of green ammonia varies between $696 to $1,024 per ton and is predominantly influenced by the choice of electrolyzers, the cost of renewable energy sources, and maintenance and operational expenditures. Furthermore, the study reveals that gray and blue ammonia production result in emissions of 2.73 and 0.28 tons of $CO_2$ equivalent per ton of ammonia, respectively, while in-situ carbon emissions from green ammonia can be considered negligible. Overall, this study underscores the potential of implementing green ammonia production utilizing geothermal or hydropower renewable energy resources as viable solutions for decarbonizing the power, industry, and transport sectors in Indonesia. Several policy recommendations aimed at overcoming existing barriers to the development of green ammonia plants in the country are also provided.

**Keywords:** Clean ammonia; Zero emission fuels; TEA analysis; Levelized cost of ammonia; Greenhouse gas emissions; Low carbon economy.

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## 1. Introduction

Ammonia is the second-largest chemical produced globally, with a capacity of 183 million tons in 2019 and projected to reach 688 million tons by 2030 (IRENA and AEA, 2022). Currently, approximately 80% of the manufactured ammonia is used as a precursor for fertilizer production, supporting half of global food production (IRENA and AEA, 2022; Rouwenhorst *et al.,* 2022). Today, there is a growing interest in utilizing ammonia as a clean alternative fuel and a carbon-neutral energy carrier (Aziz *et al.,* 2020; MacFarlane *et al.,* 2020). This interest is driven by its energy density, which is similar to that of low-grade coal (Valera-Medina *et al.,* 2018), and its inherent carbon-free nature, making it an ideal zero-emission fuel (Alfa Laval *et al.,* 2020). Such an inherent characteristic is crucial for the maritime transport industry, which currently accounts for approximately 2.89% of global greenhouse gas emissions (Liu *et al.,* 2023). Recently, the International Maritime Organization has set a target to reduce greenhouse gas emissions from this industry by 70% from 2008 levels by 2050 (IMO, 2018).

Ammonia production is an energy-intensive process that emits a significant amount of carbon dioxide ($CO_2$). In fact, it stands as the largest emitter of $CO_2$ in the chemical industry (The Royal Society, 2020; Yüzbaşıoğlu *et al.,* 2022). The conventional method of producing ammonia involves the Haber-Bosch process, which reacts nitrogen ($N_2$) with hydrogen ($H_2$) in the presence of an iron catalyst. Currently, approximately 80–86% of the hydrogen used in ammonia production is derived from natural gas through steam methane ($CH_4$) reforming (SMR) (Sazali, 2020). The ammonia produced through this process is known as gray ammonia, contributing to approximately 2% of global carbon emissions (Sandalow *et al.,* 2022).

Carbon capture and utilization or carbon capture and storage technologies can be implemented to minimize carbon emissions stemming from conventional ammonia production. Ammonia produced by combining traditional production with carbon capture and utilization or carbon capture and storage is

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referred to as blue ammonia. It is anticipated that both techniques can reduce up to 90% of the carbon emissions associated with conventional ammonia production (Raksajati *et al.,* 2013). Alternatively, ammonia can be produced entirely using renewable energy sources, resulting in virtually carbon-free production. This process is known as green ammonia production. Both blue and green ammonia play a crucial role in decarbonizing the power and transport industries by serving as clean fuel substitutes for the fossil fuels traditionally utilized in these sectors.

Recently, there has been a noteworthy surge in studies examining the techno-economic and environmental feasibility of gray, blue, and green ammonia production methods (Arnaiz del Pozo and Cloete, 2022; Lee *et al.,* 2022; Lin *et al.,* 2020; Liu *et al.,* 2020; Nayak-Luke *et al.,* 2018). Concurrently, another strand of research has delved into the aspects of country-specific potential, costs, and emissions associated with ammonia production (Guerra *et al.,* 2020; Nayak-Luke and Bañares-Alcantara, 2020; Nosherwani and Neto, 2021). This body of work collectively underscores the critical importance of methodological approaches and the need for decision support tools that can assist in effectively evaluating the techno-economic and environmental viability of different modes of ammonia production.

Recognizing such needs, this study aims to develop a spreadsheet-based decision support system for evaluating different modes of ammonia production. The system is designed with a user-friendly interface that enables ease of accessibility by non-technical experts, including policy makers and economists, to make informed decisions and conduct analysis. Further, it allows users to efficiently explore various technological options, process scenarios, and key parameters that affect the economic and environmental feasibility of different modes of ammonia production. This is particularly useful during the early stages of process design when detailed information is often limited. Subsequently, the system is used to assess the techno-economic and environmental aspects of gray, blue, and green ammonia production in Indonesia. However, it should be noted that the current system is not designed to serve as a life cycle assessment tool since it focuses solely on carbon emissions generated during the ammonia manufacturing process, rather than emissions throughout the production life cycle or supply chain.

## 2. Approach

Our approach proceeds as follows. Initially, relevant information concerning each ammonia production pathway is gathered from the literature. This information encompasses the flowsheet, reaction chemistry, and material and energy balances. Subsequently, economic and environmental assessments of the pathway are performed using the input-output material and energy flows within the process. These analyses include raw materials, energy, water, utilities, as well as other relevant process parameters. Next, sensitivity analysis studies are conducted, considering various ammonia production scenarios and process parameters in Indonesia.

### *2.1 Gray ammonia*

The most commonly used technology for gray ammonia production is the Kellogg Brown and Root (KBR) process, which accounts for approximately half of global ammonia production (KBR, 2022). Figure 1a illustrates the basic steps involved in this process (IEAGHG, 2017):

1) Conversion of a natural gas stream into syngas, which is a mixture of $H_2$, CO, $CO_2$, $CH_4$, and $H_2O$ in a primary reformer unit.
2) Conversion of $CH_4$ into $H_2$ in a secondary reformer, while simultaneously supplying air to provide the necessary source of $N_2$ for subsequent ammonia synthesis.
3) Conversion of CO and $H_2O$ into $CO_2$ and $H_2$ through water gas shift reactions in a $CO_2$ shifter.
4) Cooling of the syngas mixture in a cooling unit.
5) Separation and removal of $CO_2$ from the syngas mixture.
6) Transformation of carbon components into $CH_4$ and separation of $N_2$ and $H_2$ from the $CH_4$ mixture in a methanator unit.
7) Compression of $N_2$ and $H_2$ gases.
8) Haber-Bosch reaction between $N_2$ and $H_2$ gases to produce ammonia, with the heat generated from this reaction used to produce steam.
9) Liquefaction of ammonia gas.
10) Storage of ammonia liquid at 10–20 bar and -33 °C in a storage unit.

### *2.2 Blue ammonia*

Blue ammonia production essentially integrates a gray ammonia process with a carbon capture unit. As illustrated in Figure 1a, $CO_2$ streams separated from syngas production in the primary reformer and the $CO_2$ removal unit before the methanation process are directed to a $CO_2$ capture unit (11). Currently, about 80% of the $CO_2$ capture technology in existing ammonia plants employs an amine-based process using a primary amine, monoethanolamine (MEA) (Lee *et al.,* 2022). Other solvents such as diethanolamine (DEA) (Halim and Srinivasan, 2009) and activated methyl diethanolamine (aMDEA), which are secondary and tertiary amines, are gaining popularity due to lower energy requirements for solvent regeneration (Lee *et al.,* 2022).

Despite the advantages of DEA and aMDEA, MEA remains the most well-developed solvent, known for its superior reactivity and mass transfer capabilities (Bohrani and Wang, 2019). Therefore, this study employs MEA as the primary solvent in $CO_2$ capture technology. Simultaneously, $CO_2$ emissions from the boiler system, which is used for heat and electricity generation in the ammonia plant, also undergo amine treatment. The captured carbon is subsequently compressed and can be either sequestered into the earth's crust (i.e., carbon capture and storage) or utilized to produce valuable chemical products (i.e., carbon capture and utilization).

### *2.3 Green ammonia*

While green ammonia is also produced via the Haber-Bosch process, its main distinction from gray and blue ammonia lies in the source of $H_2$ gas, which is obtained through water electrolysis, while the $N_2$ gas is acquired from an air separation plant. In this scenario, both processes are powered by renewable energy sources, potentially leading to zero carbon emissions (see Figure 1b).

The primary water electrolysis technologies for large-scale $H_2$ production are based on alkaline and polymer electrolyte membrane (PEM) (IRENA, 2020; Nayak-Luke *et al.,* 2021). The former is a well-established hydrogen production method that has been commercially available for nearly a century (Gambou *et al.,* 2022). It involves immersing approximately 20-40% of the anode and cathode in an alkaline solution, such as KOH or NaOH in purified water with a total dissolved solid of less than

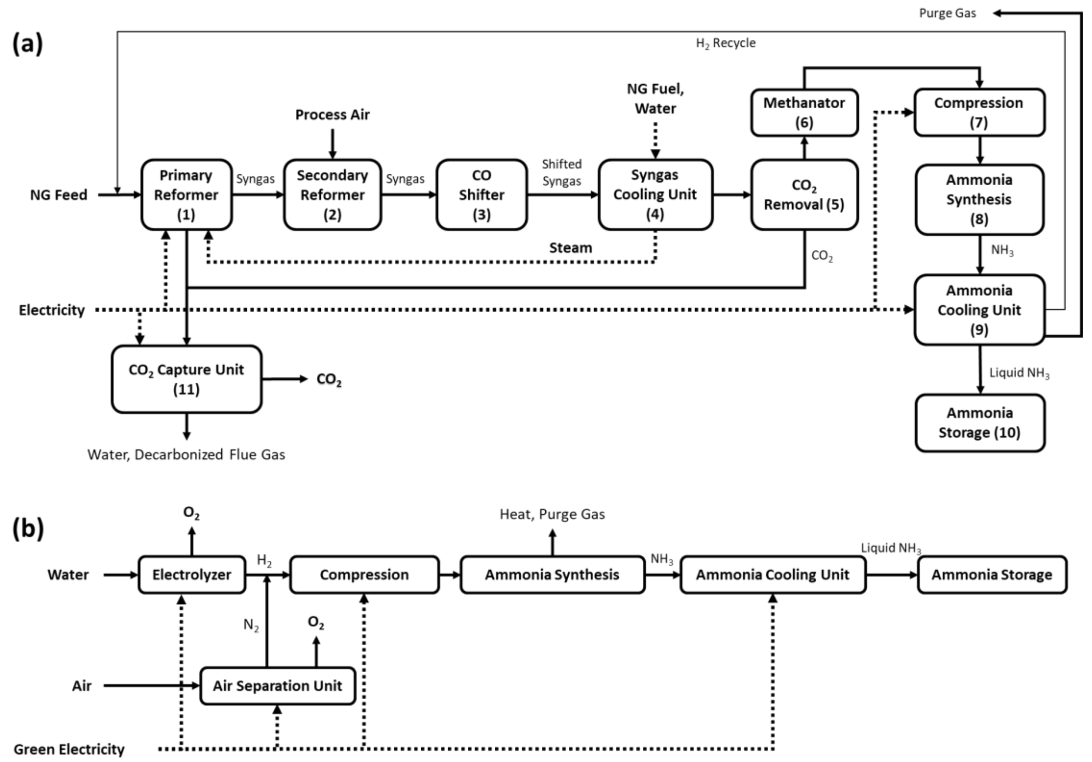


**Fig. 1** Production of (a) gray (without $CO_2$ capture unit) and blue ammonia (with $CO_2$ capture unit) and (b) green ammonia.

10 ppm (Morgan *et al.,* 2017), with a porous membrane separating the anode and cathode compartments.

On the other hand, PEM electrolysis employs deionized water to immerse the anode and cathode. Highly purified water with a TDS level of less than 0.5 ppm is necessary for PEM electrolysis. Compared to traditional alkaline electrolyzers, PEM electrolyzers have the advantage of generating higher current densities (IRENA, 2020). The use of solid polymer electrolytes also eliminates the hazards associated with the use of corrosive solutions. However, alkaline electrolyzers possess advantages in terms of maturity, cost-effectiveness and have a longevity compared to PEM electrolyzers, with a lifespan of 10 years versus 6 years (IRENA, 2020).

Three methods for obtaining nitrogen supply for ammonia plants include pressure swing adsorption, membrane separation, and cryogenic separation. In pressure swing adsoprtion, air is directed through a vessel filled with adsorbents, with carbon molecular sieve being the most commonly used (PGAE, 2018). However, as nitrogen purity decreases with increasing capacity, this method is not suitable for large-scale nitrogen production (Morgan *et al.,* 2017). Membrane separation involves conditioning air, compressing it, and passing it through non-porous hollow membranes to separate nitrogen from other components. A drawback of this method is that it requires additional treatment, such as a deoxygenation system, to achieve the nitrogen purity required for the Haber-Bosch process (Morgan *et al.,* 2017). For large-scale nitrogen separation, cryogenic separation is the most widely employed method (Spatolisano and Pellegrini, 2021). It utilizes a series of distillation processes to separate air into its primary components: nitrogen, oxygen, and rare gases. This technique can yield up to 99.99% purity nitrogen and high purity oxygen (Häring, 2008). While cryogenic air separation is more energy-intensive than the other methods, it provides a continuous and highly reliable supply of high-purity nitrogen.

### *2.4 Economic analysis*

The levelized cost of ammonia (LCOA) production is selected as the primary metric to assess and compare the economic performance of various ammonia production methods. LCOA factors in both the capital and operational expenses required per unit of ammonia produced. For gray ammonia plants, the KBR technology is specifically considered, and its total installed cost (TIC) is estimated by aggregating the expenses associated with the primary unit operations depicted in Figure 1a. Additionally, the costs related to the utility system and the balance of plant (BoP) are calculated. The BoP encompasses essential components such as the plant air supply system, boiler system, drain system, pipe connection system, and buildings (IEAGHG, 2017). In the context of blue ammonia plants, the TIC calculation also incorporates the costs associated with carbon capture and storage. For green ammonia, the TIC encompasses the purchased equipment cost (PEC) associated with the primary unit operations shown in Figure 1b. These operations include an electrolyzer module (alkaline or PEM-based), an air separation unit, a mechanical vapor compression unit, and a Haber-Bosch reactor. Furthermore, it considers the utility system and the BoP. In this case, the methodology proposed by Rivarolo *et al.* (2019) is employed to calculate the utility system and BOP costs by multiplying the PEC by a cost factor of 0.6.

The total capital cost requirement (TCR) is determined by aggregating the total plant cost (TPC), which encompasses the TIC along with a 20% contingency cost, in addition to the costs associated with spare parts cost (SPC), start-up cost (SUC), owner's cost (OC), interest charges during construction (IDC), and working capital (WC) (IEAGHG, 2017). Operational costs, such as those related to natural gas (NG), catalysts and chemicals (CC), maintenance (M), and direct labor (DL) are factored into the calculation either as part of the start-up cost or working capital cost, depending on the ammonia production methods employed. Furthermore, the discount rate (DR) is applied to account for the interest rates accrued during the construction period.

The LCOA value is calculated by dividing the total operational cost (TOC) by the amount of $NH_3$ produced per unit, as follows:

$$LCOA = \frac{Total\ Operational\ Cost\ (\$/year)}{Production\ Capacity\ (tNH_3/year)} \quad (1)$$

The TOC can be categorized into fixed and variable costs. The fixed operational cost (FOC) comprises the direct labor cost (DL), which is calculated by multiplying the number of direct laborers (NL) by the average salary (AS). Other components of the FOC include maintenance cost (M), insurance and local taxes (ILT), administration and general overheads cost (AGO), and amortization (A). On the other hand, the variable operational cost (VOC) consists of basic components such as feed materials, energy inputs, utilities, chemicals, catalysts, and other expenses that depend on the production scenarios. In the case of blue ammonia, it includes the cost of $CO_2$ capture and storage. Additionally, penalty costs such as carbon tax are incorporated in the gray and blue ammonia scenarios. For more information on input parameters and detailed formulas for calculating the LCOA, interested readers are referred to the Supplementary Information.

### 2.5 Environmental assessment

For environmental performance, onsite emissions associated with each mode of ammonia production are accounted for. This includes consideration of both direct carbon emissions (Scope 1 emissions) from the ammonia production process and indirect carbon emissions (Scope 2 emissions) from electricity generation in power plants. In the context of gray and blue ammonia scenarios, onsite emissions include the combustion of natural gas utilized as the reformer feed and the combustion of natural gas fuel within the boiler system to generate electricity. The quantity of carbon emissions from the reformer can be estimated by applying the stoichiometry of methane reforming (i.e., $CH_4 + H_2O \rightarrow 3H_2 + CO$) and the water gas shift reaction (i.e., $CO + H_2O \rightarrow CO_2 + H_2$). It is important to note that due to incomplete methane conversion, 1% (on a mole basis) of the methane feed is assumed to be released as flue gas (Lee *et al.,* 2022).

In our approach, carbon emissions from the reformer are accounted for by determining the greenhouse gas factor, which is defined as the ratio of total greenhouse gas emissions (in $kgCO_2$ equivalent) from the reformer to the quantity of natural gas used as feed (refer to Equation 2).

$$Greenhouse\ Gas\ Factor = \frac{Reformer\ Emission\ (tCO_2e/tNH_3)}{Natural\ Gas\ Feedstock\ (GJ\ NG/tNH_3)} \quad (2)$$

In this instance, normalization of carbon emissions from the reformer is performed by dividing them by the equivalent natural gas feedstock, thereby addressing variations in the energy content of natural gas. Table 1 displays the average greenhouse gas emission factors from the reformer obtained from various references.

Meanwhile, carbon emissions resulting from the electricity generation through the ammonia plant's boiler system are determined using an emission factor of 0.4 $kgCO_2e/kWh$ (equivalent to 0.111 $tCO_2e/GJ$ NG), as documented in the prior study conducted by Kazulis *et al.* (2018). These greenhouse gas factors for the reformer and boiler operations are employed to quantify the total carbon emissions produced by the gray ammonia plant.

**Table 1**
Greenhouse gas factor of emissions from the reformer.

| Reference | Natural Gas Feedstock (GJ NG/$tNH_3$) | Reformer Emissions ($tCO_2e/tNH_3$) | Greenhouse Gas Factor ($tCO_2e$/GJ NG) |
|---|---|---|---|
| Lee *et al.* (2022) | 24.49[a] | 1.4[b] | 0.0572 |
| IEAGHG (2017) | 22.34[c] | 1.293[c] | 0.0579 |
| *Greenhouse gas factor used in this study (average of the above)* | | | 0.0575 |

[a] LHV=47.1 GJ/$tNH_3$, [b] Calculated in this study from the data available from the reference, [c] LHV=46.5 GJ/$tNH_3$

In the case of blue ammonia plant, it is assumed that 90% of the $CO_2$ equivalent ($CO_2e$) emissions generated by these reformer and boiler sources will be captured using the amine process. The total emissions from blue ammonia production comprise the remaining 10% of uncaptured $CO_2$ released from the amine process as well as the indirect emissions stemming from the energy usage in the amine process, $CO_2$ dehydration and compression. Emissions associated with the energy usage for injection into the earth's crust (carbon storage) or for utilization in the production of valuable products are subject to various factors, including storage locations, storage types, and the types of products derived from $CO_2$ utilization. As these emissions fall outside the Scope 1 and Scope 2 emissions related to ammonia productions, they are not included in the present analysis.

For green ammonia production, which does not involve a combustion process, zero direct onsite carbon emissions (Scope 1) are assigned. The indirect emissions (Scope 2) from the green ammonia plant are equated to the direct carbon emissions produced by the power plant powered by renewable energy. Detailed reports on direct carbon emissions generated by various renewable energy processing plants are provided in the IPCC report (Schlömer *et al.,* 2014).

## 3. Case study: ammonia production in Indonesia

In response to the impacts of climate change, Indonesia has implemented a series of policies aimed at reducing the country's carbon emissions by 29% by 2030 and achieving net-zero emissions by 2060 (Adityo, 2022). In line with these targets, various strategies have been outlined to expedite its transition to clean energy, including the development of blue and green ammonia to decarbonize the power and industry sectors (Gunawan, 2022).

In compliance with the country's emission targets, PT Pupuk Indonesia, the largest producer of ammonia and urea fertilizer in the country, has formulated a strategic roadmap comprising

**Table 2**
Gray, blue and green ammonia production scenarios.

| Scenario | Product | Technology |
|---|---|---|
| 1 (Base Case) | Gray | NG used as feed and fuel using KBR technology. |
| 2 | Blue | Carbon capture and storage technology using amine-based solvent (MEA). |
| 3A | Green | Alkaline electrolyzer + hydropower |
| 3B | Green | Alkaline electrolyzer + geothermal |
| 3C | Green | PEM electrolyzer + hydropower |
| 3D | Green | PEM electrolyzer + geothermal |

**Table 3**
Process parameters for LCOA calculation.

| Parameters | Value | Unit |
|---|---|---|
| Plant capacity | 730,000[a] | $tNH_3$/year |
| Capacity factor | 90[b] | % |
| Discount rate (DR) | 8[b] | % |
| LHV of NG | 46.5[c] | GJ/tNG |
| Natural gas cost (NG) | 6[c] | $/GJ (LHV) |
| Raw process water cost | 0.4[d] | $/m³ |
| Conventional grid electricity cost | 64[e] | $/MWh |
| Hydropower electricity cost | 45[e] | $/MWh |
| Geothermal electricity cost | 60[e] | $/MWh |
| $CO_2$ capture from boiler cost | 70[f] | $/t$CO_2$ |
| $CO_2$ storage cost | 10.8[b] | $/t$CO_2$ |
| $CO_2$ penalty cost | 10[g] | $/t$CO_2$ |
| Individual average salary (AS) | 9,730[b] | $/person |

[a] PT Pupuk Indonesia (2021), [b] IEAGHG (2017), capacity factor accounts for operational working days per annum, [c] ESDM (2020), [d] PAM JAYA (2021), [e] Peraturan Presiden Republik Indonesia (2022), [f] Raksajati *et al.* (2013), [g] Black *et al.* (2022).

three stages of development (IESR, 2022). During the first stage, from 2023 to 2030, the company will begin the incorporation of renewable energy sources like hydropower to replace or supplement the use of fossil fuels in its ammonia and urea plants. In the medium term (2030-2040), the company will prioritize the development of blue ammonia plants by implementing carbon capture, utilization, and storage processes in their existing gray ammonia plants. Finally, in the long term (2040-2050), the company intends to construct green ammonia plants powered by hydropower or geothermal energy. This strategy aligns with the country's goal of utilizing hydropower and geothermal energy as alternative sources of power generation (IESR, 2022).

Due to its location in the Ring of Fire volcanic belt, Indonesia is rich in geothermal resources (IRENA, 2017; Yanis *et al.*, 2023). Geothermal energy can be harnessed by utilizing the heat from geothermal activity to generate electricity through steam production. An estimated geothermal potential of up to 29.4 GW exists in Indonesia (IRENA, 2017). Presently, geothermal utilization stands at 2.21 GW (Tampubolon, 2020) and is projected to reach 8.9 GW by 2030 (IRENA, 2017). Additionally, Indonesia possesses a significant hydropower potential of approximately 75 GW (IRENA, 2017). Currently, hydropower contributes around 6.54 GW to the country's electricity generation (Tampubolon, 2020) and is projected to reach 24.3 GW by 2030 (IRENA, 2017). One notable advantage of hydropower and geothermal sources over wind and solar is their reliability, as they are not reliant on specific time periods. Therefore, it is expected that hydropower and geothermal energy will dominate the country's future energy mix, meeting up to 70% of the energy demand (IRENA, 2017; Yudiartono *et al.*, 2023).

In accordance with the strategic roadmap of PT Pupuk Indonesia, a techno-economic and environmental evaluation of various ammonia production scenarios has been conducted. Considering the size of a typical ammonia plant in Indonesia, a production capacity of 2,000 $tNH_3$/day, or 730,000 $tNH_3$/year, has been selected as the design basis. An overview of the different ammonia production scenarios considered in this work is provided in Table 2, while Table 3 lists the parameters used to calculate the LCOA for different modes of ammonia production. All economic parameters are denominated in USD.

## 4. Results and discussions

### *4.1 Economic comparison*

Using the parameter values provided in the previous tables, we calculated the total capital requirement (TCR), total operational cost (TOC) – which includes both fixed and variable costs – and the LCOA for each production scenario. The results are summarized in Table 4 (for a breakdown of each cost component comprising these values, please refer to the Supplementary Information). As shown in the table, gray ammonia production exhibits the lowest total capital requirement (TCR) at $1.2 billion, followed by blue ammonia at $1.35 billion. In contrast, green ammonia production shows a significant variation in TCR, ranging from $3 billion to $4.68 billion. In this context, the alkaline-based green ammonia plant proves to be less capital intensive than the PEM-based plant.

The LCOA exhibits a similar pattern. Gray ammonia has the lowest LCOA at $297/ton, followed by blue ammonia at $390/ton, which is 1.3 times higher. In the case of green ammonia plant, the LCOA for the hydropower-based alkaline electrolyzer is $696/ton, which is 2.3 times higher than that of gray ammonia. Meanwhile, geothermal-based alkaline electrolyzer yields a LCOA of $835/ton, approximately 2.8 times higher than gray ammonia. This higher cost can be attributed to the expense of electricity generation using geothermal sources ($60/kWh), which is higher than that of hydropower ($45/kWh). The LCOA for the hydropower-based PEM electrolyzer is 2.9 times higher than gray ammonia at $876/ton, while PEM powered by geothermal results in a higher LCOA of $1,024/ton, which is 3.4 times higher. These findings align with the values reported in IRENA and AEA (2022), where LCOA ranges from $110/ton to $340/ton for gray ammonia, $360/ton to $450/ton for blue ammonia, and $720/ton to $1,400/ton for green ammonia. The LCOA values obtained from this study are thus in good agreement with those industry estimates.

**Table 4**
TCR, TOC and LCOA values for different production scenarios.

| | Scenario-1 (Gray) | Scenario-2 (Blue) | Scenario-3A (Alkaline-Hydro) | Scenario-3B (Alkaline-Geo) | Scenario-3C (PEM-Hydro) | Scenario-3D (PEM-Geo) |
|---|---|---|---|---|---|---|
| TCR ($) | 1,208,200,795 | 1,354,953,838 | 3,067,296,170 | 3,067,296,170 | 4,681,430,018 | 4,681,430,018 |
| FOC ($) | 27,918,122 | 31,316,916 | 155,684,370 | 155,684,370 | 281,981,543 | 281,981,543 |
| VOC ($) | 167,327,923 | 224,677,828 | 301,629,604 | 393,028,816 | 293,225,312 | 390,484,307 |
| TOC ($) | 195,246,046 | 255,994,744 | 457,313,974 | 548,713,186 | 575,206,855 | 672,465,850 |
| LCOA ($/$tNH_3$) | 297 | 390 | 696 | 835 | 876 | 1,024 |

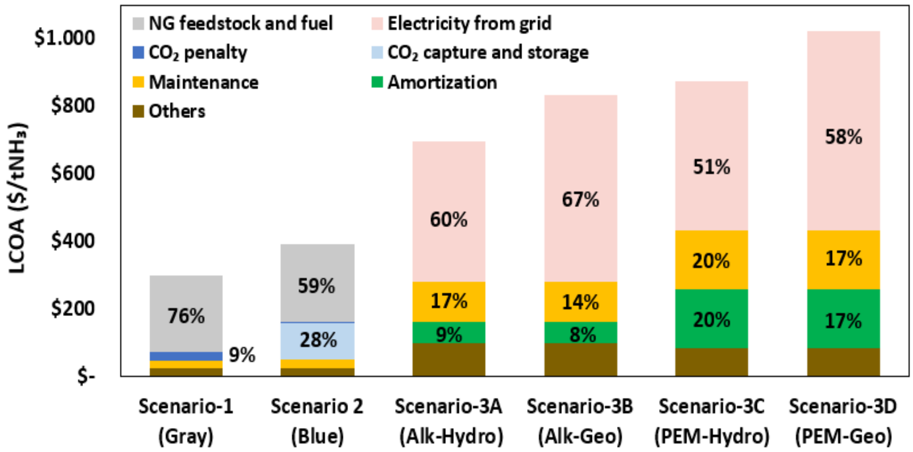


**Fig. 2** LCOA with cost components breakdown.

Figure 2 provides a breakdown of the components contributing to the LCOA for all the scenarios examined in this study. In Scenario 1 (gray ammonia), the LCOA is primarily influenced by the cost of natural gas (NG), accounting for approximately 76% of the total. Consequently, it is susceptible to fluctuations in natural gas prices, which can significantly impact the overall LCOA. For Scenario 2 (blue ammonia), the LCOA is higher due to the inclusion of $CO_2$ capture cost ($70/t$CO_2$) (Raksajati *et al.,* 2013) and storage cost ($10/t$CO_2$) (IEAGHG, 2017). In this case, the LCOA of blue ammonia is dominated by the cost of natural gas (~59%), followed by the cost of carbon capture and storage (~28%).

In the case of green ammonia (Scenarios 3A-D), the LCOA is primarily driven by the cost of electricity, representing approximately 51-67% of the total. This is because green ammonia production relies on electrolyzers for hydrogen supply. The maintenance cost of the electrolyzers contributes around 14-20% to the LCOA, while amortization costs account for approximately 8-20%. Importantly, green ammonia production does not incur $CO_2$ penalty costs or carbon capture and storage costs since it generates minimal or nearly zero carbon emissions.

In summary, these breakdowns emphasize the principal cost drivers for each ammonia production scenario, with natural gas costs playing a significant role for gray and blue ammonia, while electricity costs are the predominant factor for green ammonia.

### *4.2 Carbon emissions comparison*

In assessing the environmental impact, onsite carbon emissions, measured in t$CO_2$e/t$NH_3$ product, were calculated for each scenario. For gray and blue ammonia, the greenhouse gas factor of 0.0575 t$CO_2$e/GJ NG (see Table 1) was used to determine the emissions from the reformer. For boiler emissions, the greenhouse gas emission factor of 0.111 t$CO_2$e/GJ NG was applied (Kazulis *et al.,* 2018).

Table 5 presents the total onsite carbon emissions (Scope 1 and Scope 2) for all scenarios. As shown in the table, the reformer unit of gray ammonia production produces about 1.52 t$CO_2$e/t$NH_3$ which aligns with the findings reported by Gezerman (2021). In total, gray ammonia production results in

**Table 5**
Carbon avoidance cost.

| | Gray Ammonia | Blue Ammonia | Green Ammonia |
|---|---|---|---|
| Carbon emission due to ammonia production (Scope 1) (t$CO_2$e/t$NH_3$) | 1.52 | 0.152 (90% avoided) | - |
| Carbon emission due to power generation (Scope 2) (t$CO_2$e/t$NH_3$) | 1.21[a] | 0.128[b] (90% avoided) | 0[c] |
| Total carbon emission (t$CO_2$e/t$NH_3$) | 2.73 | 0.28 | 0 |
| LCOA ($/t$NH_3$) | 297 | 390 (+31%) | 696 - 1,024 (+134% to 245%) (depending on green ammonia scenario) |
| Increased LCOA ($/t$CO_2$e avoided) | - | 37 | 146 - 266 (depending on green ammonia scenario) |

[a] Carbon emission due to energy use for the ammonia production process.
[b] Carbon emission (10% uncaptured $CO_2$) due to energy use for the ammonia production process, amine process, and $CO_2$ dehydration and compression process. Indirect emissions from $CO_2$ injection into the earth's crust or $CO_2$ conversion into valuable products are excluded.
[c] Carbon emission from the power plants running on hydropower or geothermal are negligible (Schlömer *et al.*, 2014).

an onsite carbon emission of 2.73 $tCO_2e/tNH_3$. This value aligns well with the findings reported by Brightling (2018). In the case of blue ammonia, the carbon emissions are significantly reduced to 0.28 $tCO_2e/tNH_3$, representing a substantial reduction compared to gray ammonia. This reduction is achieved by assuming the capture of 90% of purely $CO_2$ from the reformer and the boiler system using amine technology.

In the context of green ammonia production, zero carbon emissions can be assumed, as there are no direct and indirect carbon emissions during the production process. However, this approach results in a considerably higher LCOA. Such substantial increase in LCOA for green ammonia is put into perspective by calculating the carbon avoidance cost. The results are presented in Table 5. As can be seen, the LCOA increases by \$37/$tCO_2e$ avoided for blue ammonia, and by \$146/$tCO_2e$ to \$266/$tCO_2e$ avoided for green ammonia. This result underscores the importance of reducing the carbon capture cost to enhance the cost competitiveness of blue ammonia. Furthermore, it highlights that while green ammonia represents the best climate solution, its current cost remains a significant barrier to widespread deployment.

Overall, this analysis illustrates the carbon emissions linked to each ammonia production scenario, with blue ammonia showing notable reductions, and green ammonia providing emission-free production at an elevated cost in comparison to gray ammonia.

### *4.3 Sensitivity analysis of LCOA*

A sensitivity analysis study was conducted to assess the impacts of the following parameters on the LCOA: (i) natural gas cost, (ii) $CO_2$ penalty cost, (iii) $CO_2$ storage cost, (iv) renewable energy source cost, (v) water cost, and (vi) maintenance cost. The parameter ranges were determined based on a previous study by Arnaiz del Pozo and Cloete (2022) for natural gas, penalty, carbon capture and storage costs, while renewable energy and water costs were taken from reported values for Indonesia (PAM JAYA, 2021; Peraturan Presiden Republik Indonesia, 2022). The range for maintenance cost parameters was obtained from Dias *et al.* (2020).

Table 6 presents the results of the sensitivity analysis study. It highlights that variations in natural gas price and carbon penalty cost have a significant impact on the cost of gray ammonia. An increase in natural gas price from \$4.5 to \$8.5 raises the LCOA of gray ammonia from \$249/ton to \$396/ton, representing a +59%. Similarly, an increase in the penalty cost from \$0 to \$200 results in an LCOA increase for gray ammonia from \$278/ton to \$809/ton, indicating a +191%.

In the case of blue ammonia, an increase in natural gas price from \$4.5 to \$8.5 results in an LCOA increase for blue ammonia from \$339/ton to \$486/ton (+43.3%). The impact of $CO_2$ penalty cost on LCOA is much lower (+13.5% compared to +191% in gray), as most of the carbon emissions are captured. The LCOA of blue ammonia is moderately affected by carbon capture and storage cost, with an increase in the carbon storage cost from \$10 to \$30 leading to an LCOA increase from \$392/ton to \$440/ton (+12.2%).

For green ammonia, the cost of renewable electricity and maintenance has a significant effect on the LCOA, ranging from \$552/ton to \$1,651/ton and from \$652/ton to \$1,004/ton, respectively. The impact of water cost on the LCOA of green ammonia is relatively small, despite it being one of the main raw materials.

Overall, this sensitivity analysis study reveals three key findings. First, it demonstrates that blue ammonia maintains a relatively stable LCOA compared to gray and green ammonia. The LCOA of blue ammonia varies between \$339/ton and \$486/ton, whereas for gray ammonia, the range is broader, spanning from \$249/ton to \$809/ton. In the case of green ammonia produced using alkaline electrolyzers, the LCOA range is even wider, from \$552/ton to \$1,424/ton, while for PEM electrolyzers, it spans from \$722/ton to \$1,651/ton. Second, a substantial increase in the carbon penalty cost can enhance the competitiveness for both blue and green ammonia, making them preferable to gray ammonia. Lastly, a decrease in the cost of renewable energy would significantly impact the competitiveness of green ammonia.

**Table 6**
Sensitivity analysis of LCOA.

| Parameter | Unit Cost[a] | LCOA (\$/$tNH_3$) | | | |
|---|---|---|---|---|---|
| | | Gray | Blue | Green (Alkaline) | Green (PEM) |
| Natural gas cost (\$/tNG) | 4.5 | 249 | 339 | - | - |
| | 8.5 | 396 (+59%) | 486 (+43.3%) | - | - |
| $CO_2$ penalty cost (\$/$tCO_2$ emitted) | 0 | 278 | 392 | - | - |
| | 200 | 809 (+191%) | 445 (+13.5%) | - | - |
| $CO_2$ storage cost (\$/$tCO_2$ stored) | 10 | - | 392 | - | - |
| | 30 | - | 440 (+12.2%) | - | - |
| Renewable energy cost (\$/MWh) | 29.47 | - | - | 552 | 722 |
| | 123.53 | - | - | 1,424 (+158%) | 1,651 (+128.7%) |
| Water cost (\$/$m^3$) | 0.4 | 304 | 394 | 696 | 876 |
| | 1.3 | 305 (+0.33%) | 394 (+0.0%) | 698 (+0.29%) | 878 (+0.23%) |
| Maintenance cost | 2% | 313 | 404 | 652 | 811 |
| | 5% | 365 (+16.6%) | 462 (+14.4%) | 785 (+20.4%) | 1,004 (+23.8%) |

[a] The minimum and maximum range of values for this sensitivity analysis study.

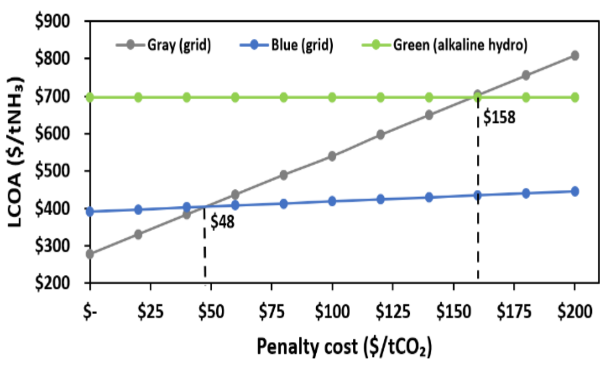


**Fig. 3** Impact of penalty cost (carbon tax) on LCOA.

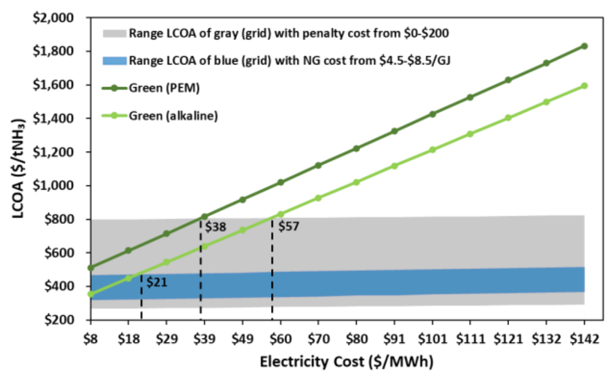


**Fig. 4** Impact of hydropower electricity cost on LCOA of green ammonia.

*4.4 Towards green ammonia*

Below are several factors that will incentivize the development of green ammonia production in Indonesia.

*4.4.1. Increased carbon tax*

In pursuit of its net-zero emissions target by 2060, the Indonesian government has recently issued a presidential decree that aims to phase out its fleet of coal-based power plants by 2050 (Peraturan Presiden Republik Indonesia, 2022). Given this context, there is an expectation of significant investment in blue and green ammonia production facilities to provide clean fuels.

Another important tool for expediting the development of blue and green ammonia facilities in the country is the implementation of carbon penalties or carbon taxes. Although the current carbon penalty imposed in Indonesia is quite low at $6/tCO_2$, there is an expectation of a substantial increase in the penalty cost in the coming years, following the recommendation by the International Monetary Fund (IMF) of implementing a penalty cost of $75/tCO_2$ by 2030 (Black *et al.,* 2022). In fact, several European countries have already imposed penalty costs exceeding $90/tCO_2$ (Black *et al.,* 2022).

As shown in Table 4, the LCOA for gray ammonia in Indonesia stands at $297/ton with a penalty cost of $10/tCO_2$. With a higher penalty cost of $75/tCO_2$, the LCOA would increase to $475/ton, and at $90/tCO_2$, it would further rise to $515/ton. Given this significantly higher LCOA, gray ammonia becomes less competitive when compared to blue and green ammonia. This trend is clearly illustrated in Figure 3, where the LCOA of blue ammonia aligns with that of gray ammonia when the penalty cost reaches $48/tCO_2$.

In the case of green ammonia, its LCOA becomes more cost-effective than gray ammonia when the imposed carbon penalty cost reaches $158/tCO_2$. These findings emphasize the importance of progressively increasing carbon penalty costs to incentivize the production of low-carbon blue and eventually green ammonia as they become more economically competitive.

*4.4.2. Reduced renewable electricity price*

One current challenge hindering the widespread adoption of green ammonia production is the cost of electrolysis technology, which remains high and is strongly influenced by renewable energy expenses. With the current delivered price of green ammonia ranging from $742 to $794 per ton in various regions (S&P Global, 2023), it is essential that the levelized cost of green ammonia falls below these values for investment to be profitable. Presently, this goal is achievable primarily through technology utilizing alkaline electrolyzer powered by hydro energy.

As hydropower represents one of the most promising renewable energy sources in Indonesia due to its abundant and non-intermittent availability, the government has established a maximum target price of $37.6/MWh for national hydropower electricity to stimulate investments in technology relying on hydropower (Peraturan Presiden Republik Indonesia, 2022). By using this price as a reference, the levelized cost of green ammonia in Indonesia has the potential to decrease to $627/ton, which is notably attractive.

Figure 4 illustrates the impact of hydropower electricity prices on the LCOA of green ammonia. It demonstrates that green ammonia production using an alkaline electrolyzer can attain competitiveness similar to blue ammonia and gray ammonia, provided that the cost of renewable energy can be lowered to $21/MWh. However, achieving this cost reduction may require government assistance in the form of subsidies, investment incentives, tax cuts, and other financial support mechanisms (Abidin *et.al.*, 2020).

*4.4.3. Sales of oxygen byproduct*

Another significant aspect of green ammonia production is the generation of high-purity oxygen as the byproduct of the water electrolysis and cryogenic distillation processes. For instance, in a 2,000 tpd green ammonia plant with a capacity factor of 90%, it is possible to produce 2,520 tpd of oxygen from the electrolyzer unit and 393 tpd of oxygen from the distillation unit. In 2021, the import price of oxygen in the EU stood at $0.2/m^3$, equivalent to $140/tO_2$ (Indexbox, 2022). This could potentially result in additional annual revenue of $133,968,870. Such revenue can be used to offset the LCOA of green ammonia, which ranges from $627-802/ton (based on a renewable energy cost of $37.6/MWh), reducing it to the range of $423-598/ton (a reduction of 25-32%). However, this reduction depends on the selling price of oxygen, which fluctuates with market conditions.

*4.4.4. Reduced electrolyzer cost*

Lastly, there is potential to reduce the capital costs, as well as the corresponding maintenance and amortization costs of the electrolyzer, by lowering its stack cost. Scaling up the manufacturing of electrolyzer stacks has the potential to reduce stack costs by 60-70% (IRENA, 2020; Nayak-Luke *et al.,* 2021). This underscores the need for technological advancements in this sector. Therefore, it is essential to engage in collaborative research and development initiatives with leading organizations, and partnerships and joint investment projects with developed countries to enhance energy infrastructures and improve electrolyzer performance. One example of such collaboration is the joint project currently being explored by PLN – the Indonesian State Electricity Company – and the French Hydrogen Association to develop a green hydrogen plant in Indonesia using an electrolyzer powered by renewable energy sources (Energy News, 2023).

Our calculation shows that by combining the revenue from the oxygen sales and the reduced stack cost, the LCOA for green ammonia could potentially be lowered to a range of $298-373/ton, representing a reduction of 35-40%. Additionally, improved management and optimization of energy systems can enhance the overall economics of green ammonia production, making it more competitive and economically attractive (Aziz *et al.,* 2020).

### *4.5 Green ammonia and Sustainable Development Goals*

Green ammonia plays a crucial role in achieving the United Nations Sustainable Development Goals (SDGs). As the global population continues to grow, demand for energy rises. Transitioning from conventional gray ammonia production to green ammonia will significantly contribute to climate action (SDG 13) and clean energy supply (SDG 7) goals. Furthermore, the availability of green ammonia, a key component in fertilizer production, is vital for global food production, thus contributing to the goals of zero-hunger (SDG 2) and good health and well-being of the society (SDG 3). Finally, research and development activities, along with improvement in the manufacturing process, to address the high cost of electrolyzer production not only drive technological innovation and infrastructure investment in this industry (SDG 9) but also create jobs and stimulate economic growth for the country (SDG 8).

## 5 Conclusions

A spreadsheet-based decision support system has been developed to assess the techno-economic and environmental aspects of various modes of ammonia production. The system was applied to a case study applicable to Indonesia, yielding valuable insights into the cost and emission profiles of different ammonia production scenarios.

In the sensitivity analysis study, a wide range of LCOA for green ammonia is highlighted, with a span from $552/ton to $1,651/ton, primarily influenced by the cost of renewable energy sources. Several measures can be taken to narrow this gap and make green ammonia as competitive as blue ammonia. These measures include reducing the electrolyzers cost, offering subsidies to decrease the expense of renewable energy sources, selling the oxygen byproduct, and optimizing the energy system to enhance overall system efficiency. By implementing these measures, the LCOA of green ammonia production using alkaline electrolyzers could potentially be reduced to $298/ton, while for PEM electrolyzers, an LCOA of $373/ton would become possible.

Overall, our system facilitates a quick assessment of various ammonia production scenarios in Indonesia, providing insights into the stability of LCOA, carbon emissions, and the factors influencing cost competitiveness. It also underscores the feasibility of deploying blue ammonia production and delineates strategies for improving the cost-effectiveness of green ammonia as a viable solution for climate change mitigation. However, it is important to acknowledge the limitations of our system, which is currently applicable solely to economic and environmental assessments within the boundaries of ammonia production. Our future work will incorporate the life cycle and supply chain aspects.

### Author contributions

All authors contributed to the study conception, design methodology and writing draft preparation. Material preparation, data collection and analysis were performed by MT, IS and GAS. IS and GAS contributed to visualization. MT, AA and IH contributed to review and editing. All authors have read and approved the final manuscript.

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### Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

Enquiries about data availability should be directed to the authors.

## References

Abidin, M. Z., Rosdiana, H., and Salomo, R. V. (2020). Tax Incentive Policy for Geothermal Development: A Comparative Analysis in ASEAN. *International Journal of Renewable Energy Development,* 9(1), 53-62. https://doi.org/10.14710/ijred.9.1.53-62

Adityo, A. (2022). Indonesia's Grand Experiment in Implementing a Fair and Acceptable Carbon Tax. Indonesia Post-Pandemic Outlook: Social Perspectives, 3, 35-55. https://doi.org/10.55981/brin.536

Alfa Laval, Hafnia, Haldor Topsoe, Vestas, and Siemens Gamesa. (2020). Ammonfuel – An Industrial View of Ammonia as a Marine Fuel. https://www.alfalaval.com/industries/marine-transportation/marine/fuel-conditioning/ammonia-as-fuel/

Arnaiz del Pozo, C. and Cloete, S. (2022). Techno-Economic Assessment of Blue and Green Ammonia as Energy Carriers in a Low-Carbon Future. *Energy Conversion and Management*, 255, 115312. https://doi.org/10.1016/j.enconman.2022.115312

Aziz, M., Wijayanta, A.T., and Nandiyanto. A.B.D. (2020). Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization. *Energies*, 13(12), 3062. https://doi.org/10.3390/en13123062

Black, S., Parry, I., and Zhunussova, K. (2022). Carbon Taxes or Emissions Trading Systems? Instrument Choice and Design. *IMF Staff Climate Note 2022/006.* https://www.imf.org/-/media/Files/Publications/Staff-Climate-Notes/2022/English/CLNEA2022006.ashx

Bohrani, T.N., and Wang, M. (2019). Role of Solvents in $CO_2$ Capture Processes: The Review of Selection and Design Methods. *Renewable and Sustainable Energy Reviews*, 114, 109299. https://doi.org/10.1016/j.rser.2019.109299

Brightling, J.R. (2018). Ammonia and The Fertiliser Industry: The Development of Ammonia at Billingham. *Johnson Matthey Technology Review,* 62(1), 32-47. https://doi.org/10.1595/205651318X696341

Dias, V., Pochet, M., Contino, F., and Jeanmart, H. (2020). Energy and Economic Costs of Chemical Storage. *Frontiers in Mechanical Engineering*, 6, 21. https://doi.org/10.3389/fmech.2020.00021

Energy News. (2023). PLN and French Hydrogen Association Collaborate to Develop Green Hydrogen in Indonesia. https://energynews.biz/pln-and-french-hydrogen-association-collaborate-to-develop-green-hydrogen-in-indonesia/

ESDM. (2020). Permen ESDM tentang Tata Cara Penetapan Pengguna dan Harga Gas Bumi Tertentu di Bidang Industri" https://www.esdm.go.id/id/berita-unit/direktorat-jenderal-minyak-dan-gas-bumi/permen-esdm-tentang-tata-cara-penetapan-pengguna-dan-harga-gas-bumi-tertentu-di-bidang-industri.

Gambou, F., Guilbert, D., Zasadzinski, M., and Rafaralahy, H. (2022). A Comprehensive Survey of Alkaline Electrolyzer Modeling: Electrical Domain and Specific Electrolyte Conductivity. *Energies*, 15(9), 3452. https://doi.org/10.3390/en15093452

Gezerman, A.O. (2021). A Critical Assessment of Green Ammonia Production and Ammonia Production Technologies. *Toros Agri & Industry* 71, 57-66. https://doi.org/10.15255/KUI.2021.013

Guerra, C.F., Reyes-Bozo, L., Vyhmeister, E., and Caparros. M. (2020). Technical-Economic Analysis for a Green Ammonia Production Plant in Chile and Its Subsequent Transport to Japan. *Renewable Energy* 157(10), 404-414. https://doi.org/10.1016/j.renene.2020.05.041

Gunawan, D. (2022). Unlocking the Potential of Hydrogen in Indonesia. Indonesia Post-Pandemic Outlook: Strategy Towards Net-Zero Emissions by 2060 from the Renewables and Carbon-Neutral Energy Perspectives 11, 209-235. https://doi.org/10.55981/brin.562.c11

Halim, I., and Srinivasan, R. (2009). A Simulation-Optimization Framework for Efficient $CO_2$ Capture using Amine Absorption. *Chemical Engineering Transactions* 18, 273-278. https://doi.org/10.3303/CET0918043

Häring, H.W. (2008). Industrial Gases Processing. München, Germany: Wiley-VCH.

IEAGHG. (2017). Techno-Economic Evaluation of Hyco Plant Integrated to Ammonia/Urea or Methanol Production with CCS. https://ieaghg.org/exco_docs/2017-03.pdf

IESR. (2022). Indonesia Energy Transition Outlook 2023. https://iesr.or.id/wp-content/uploads/2022/12/Indonesia-Energy-Transition-Outlook_2023.pdf.

IMO. (2018). IMO's Work to Cut GHG Emissions from Ships. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx.

Indexbox. (2022). Oxygen Market Report: Size, Production, Trends and Forecast to 2030. https://www.globenewswire.com/en/news-release/2022/04/12/2420689/0/en/Oxygen-Market-Report-Size-Production-Trends-and-Forecast-to-2030-IndexBox.html

IRENA and AEA. (2022). Innovation outlook: renewable ammonia. International Renewable Energy Agency, Abu Dhabi, Ammonia Energy Association, Brooklyn.

IRENA. (2017). Renewable Energy Prospects: Indonesia, a REmap Analysis, International Renewable Energy Agency, Abu Dhabi.

IRENA. (2020). Green Hydrogen Cost Reduction: Scaling Up Electrolyzers to Meet the 1.5℃ Climate Goal. International Renewable Energy Agency, Abu Dhabi.

Kazulis, V., Vigants, H., Veidenbergs, I., and Blumberga, D. (2018). Biomass and Natural Gas Co-Firing – Evaluation of GHG Emissions. *Energy Procedia* 147, 558-565. https://doi.org/10.1016/j.egypro.2018.07.071

KBR. (2022). KBR Ammonia Cracking a Technology for Dissociating Ammonia into Hydrogen and Nitrogen. https://www.kbr.com/sites/default/files/2022-09/Ammonia-Cracking-Handout.pdf

Lee, K., Liu, X., Vyawahare, P., Sun, P., Elgowainy, A., and Wanga, M. (2022). Techno-Economic Performances and Life Cycle Greenhouse Gas Emissions of Various Ammonia Production Pathways Including Conventional, Carbon-Capturing, Nuclear-Powered, and Renewable Production. *Green Chemistry* 24(12), 4830-4844. https://doi.org/10.1039/D2GC00843B

Lin, B., Wiesner, T.F., and Malmali, M. (2020). Performance of a Small-Scale Haber Process: a Techno-Economic Analysis. *ACS Sustainable Chemistry & Engineering* 8(41),15517-15531. https://pubs.acs.org/doi/10.1021/acssuschemeng.0c04313?goto=supporting-info

Liu, H., Mao, Z., and Li, X. (2023). Analysis of International Shipping Emissions Reduction Policy and China's Participation. *Frontiers in Marine Science* 10, 3389. https://doi.org/10.3389/fmars.2023.1093533

Liu, X., Elgowainy, A., and Wang, M. (2020) Life Cycle Energy Use and Greenhouse Gas Emissions of Ammonia Production from Renewable Resources and Industrial By-Products. *Green Chemistry* 22(17), 5751-5761. https://doi.org/10.1039/D0GC02301A

MacFarlane, D.R., Cherepanov, P.V., Choi, J., Suryanto, B.H.R., Hodgetts, R.Y., Bakker, J.M., Vallana, F.M.F., and Simonov, A.N. (2020). A Roadmap to the Ammonia Economy. *Joule* 4, 1186–1205. https://doi.org/10.1016/j.joule.2020.04.004

Morgan, E.R., Manwell, J.F., and McGowan, J.G. (2017). Sustainable Ammonia Production from U.S. Offshore Wind Farms: A Techno-Economic Review. *ACS Sustainable Chemistry & Engineering* 5(11), 9554-9567. https://doi.org/10.1021/acssuschemeng.7b02070

Nayak-Luke, R.M., Bañares-Alcántara, R., and Wilkinson, I. (2018). "Green" Ammonia: Impact of Renewable Energy Intermittency on Plant Sizing and Levelized Cost of Ammonia. *Industrial & Engineering Chemistry Research* 57(43), 14607-14616. https://doi.org/10.1021/acs.iecr.8b02447

Nayak-Luke, R.M., and Bañares-Alcántara, R. (2020). Techno-Economic Viability of Islanded Green Ammonia as a Carbon-Free Energy Vector and as a Substitute for Conventional Production. *Energy & Environmental Science* 13(9), 2957-2966. https://doi.org/10.1039/D0EE01707H

Nayak-Luke, R.M., Forbes, C., Cesaro, Z., Banares-Alcantara, R., and Rouwenhorst, K.H.R. (2021). Techno-Economic Aspects of Production, Storage and Distribution of Ammonia. Techno-Economic Challenges of Green Ammonia as an Energy Vector 8, 191-207. https://doi.org/10.1016/B978-0-12-820560-0.00008-4

Nosherwani, S.A., and Neto, R.C. (2021). Techno-Economic Assessment of Commercial Ammonia Synthesis Methods in Coastal Areas of Germany. *Journal of Energy Storage* 34, 102201. https://doi.org/10.1016/j.est.2020.102201

PAM JAYA. (2021). Annual Report 2021. https://ppid.pamjaya.co.id/assets/laporan/LPE20220928044539899.pdf

Peraturan Presiden Republik Indonesia. (2022). Percepatan Pengembangan Energi Terbarukan untuk Penyediaan Tenaga Listrik. https://peraturan.bpk.go.id/Home/Details/225308/perpres-no-112-tahun-2022

PGAE. (2018). Pressure Swing Adsorption Technical Analysis. https://www.pge.com/pge_global/common/pdfs/for-our-business-partners/ interconnection-renewables/interconnections-renewables/PressureSwingAdsorption_ TechnicalAnalysis.pdf

PT Pupuk Indonesia. (2021). Annual Report PT Pupuk Indonesia. BUMN. https://www.pupuk-indonesia.com/storage/654/6375a37377916_62ba7b7617a23_20220531---PTPI-21---FULL---OJK1654040816.pdf

Raksajati, A., Wiley, D., and Ho, M.T. (2013). Reducing the Cost of $CO_2$ Capture from Flue Gases using Aqueous Chemical Absorption. *Industrial & Engineering Chemistry Research* 52(47), 16887-16901. https://doi.org/10.1021/ie402185h

Rivarolo, M., Riveros-Godoy, G., Magistri, L., and Massardo, A.F. (2019). Clean Hydrogen and Ammonia Synthesis in Paraguay from the Itaipu 14 GW Hydroelectric Plant. *ChemEngineering* 3, 87. http://dx.doi.org/10.3390/chemengineering3040087

Rouwenhorst, K.H.R., Travis, A.S., and Lefferts, L. (2022). 1921–2021: A Century of Renewable Ammonia Synthesis. *Sustainable Chemistry* 3(2), 149-171. https://doi.org/10.3390/suschem3020011

S&P Global. (2023). Interactive: Ammonia Price Chart. https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/051023-interactive-ammonia-price-chart-natural-gas-feedstock-europe-usgc-black-sea

Sandalow, D., Aines, R., Fan, Z., Friedmann, J., McCormick, C., Merz, A., and Scown, C. (2022). Low-Carbon Ammonia Roadmap. ICEF Innovation Roadmap Project.

Sazali, N. (2020). Emerging Technologies by Hydrogen: A Review. *International Journal of Hydrogen Energy* 45(38), 18753-18771. https://doi.org/10.1016/j.ijhydene.2020.05.021

Spatolisano, E., and Pellegrini, L.A. (2021). $CO_2$-Tolerant Cryogenic Nitrogen Rejection Schemes: Analysis of Their Performances. *Industrial & Engineering Chemistry Research*, 60, 4420-4429. https://dx.doi.org/10.1021/acs.iecr.0c06189?ref=pdf

Schlömer, S., Bruckner, T., Fulton, L., Hertwich, E., McKinnon, A., Perczyk, D., Roy, J., Schaeffer, R., Sims, R., Smith, P., and Wiser, R. (2014). Annex III: Technology-Specific Cost and Performance Parameters. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., and Minx, J.C. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

The Royal Society. (2020). Ammonia: Zero-Carbon Fertiliser, Fuel, and Energy Store. The Royal Society. https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf

Valera-Medina, A., Xiao, H., Owen-Jones, M., David, W.I.F., and Bowen, P.J. (2018). Ammonia for Power. *Progress in Energy and Combustion Science* 69, 63-102. https://doi.org/10.1016/j.pecs.2018.07.001

World Salaries. (2023). Average Salary in Indonesia for 2023. https://worldsalaries.com/average-salary-in-indonesia

Yanis, M., Zaini, N., Novari, I., Abdullah, F., Dewanto, B. G., Isa, M., Marwan, M., Zainal, M., & Abdurrahman, A. (2023). Monitoring of Heat Flux Energy in the Northernmost Part of Sumatra Volcano Using Landsat 8 and Meteorological Data. *International Journal of Renewable Energy Development*, 12(1), 55-65. https://doi.org/10.14710/ijred.2023.47048

Yudiartono, Y., Windarta, J., & Adiarso, A. (2023). Sustainable Long-Term Energy Supply and Demand: The Gradual Transition to a New and Renewable Energy System in Indonesia by 2050. *International Journal of Renewable Energy Development*, 12(2), 419-429. https://doi.org/10.14710/ijred.2023.50361

Yüzbaşıoğlu, A.E., Avşar, C., and Gezerman, A.O. (2022). The Current Situation in the Use of Ammonia as a Sustainable Energy Source and its Industrial Potential. *Current Research in Green and Sustainable Chemistry* 5, 100307. https://doi.org/10.1016/j.crgsc.2022.100307

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