Techno-economic analysis of a small-scale power-to-green urea plant

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Abstract. Power-to-green urea is the concept of urea production using hydrogen from photovoltaic (PV)-electrolysis; a promising option for remote area that do not have natural gas reserves. In this study techno-economic analysis of a small-scaled power-to-green urea plant is conducted with the purpose of obtaining energy efficiency of the system, specific energy consumption, and urea price. Process simulation is carried out by using Aspen Plus and green urea price is calculated using cash flow with 4 schemes. Scheme 1 uses investment cost of technology in 2019, scheme 2 is modification of scheme 1 with additional revenue through clean development mechanisms (CDM), scheme 3 uses investment cost of technology in 2030 and 2050, and scheme 4 is a combination of scheme 2 and 3. The obtained result shows the system efficiency of 7.9% and specific energy consumption of 109 GJ/MT urea. The price of green urea with Scheme 1, 2, 3, and 4 in order are 2342, 2320, 2026 and 1704, as well as 2004 and 1682 USD/MT urea, respectively. Power-to-green urea could not compete economically with conventional large-scale urea; however, due to its stable price and easily acquired raw material it is still highly relevant for remote areas in the future.

1. Introduction
Currently, urea is the world’s most consumed fertilizer, meanwhile, in Indonesia, it comprises 50% of the total fertilizer stock in 2019 [1][2]. In order to produce urea, ammonia is required and its production process contributes to 1.8% of both global energy output and carbon dioxide emission annually, making it the largest carbon dioxide emitter of the chemical industry [3]. The underlying reason for this is that hydrogen, the building block for ammonia, is synthesized through steam methane reforming that emits a high carbon dioxide level.

In recent years, the movement towards green chemical industry is apparent, the identification of commodity chemicals with high carbon emission paves the way towards focusing upcoming researches towards greening the ammonia-based fertilizer industry [4]. An all electrical ammonia plant has been reported together with a plausible all-solar ammonia production; however, the latter is still hypothetical and not fit for commercial ammonia production [5]. The techno-economic study is fairly widespread regarding green ammonia; wind-powered electrolysis coupled with Haber-Bosch process was found to yield levelized cost of ammonia (LCOA) three times higher its conventional counterpart [6], another study conducted by the South Australian Government vary the utilization of electrolysis-sourced hydrogen and evaluate the economics through net present worth (NPV) yielding negative NPV for large-scale ammonia production even when the plant is built in 2027 [7]. Apart from economic aspect, energy consumption and system efficiency from renewable power to ammonia is also present; generally, power from wind results in higher system efficiency in comparison to solar;
however, both have lower system efficiency and higher energy consumption per metric ton ammonia [4][8].

Based on previous studies, the system boundary starts from either solar or wind power source to the ammonia synthesis process. There have been no studies that have reviewed up to the urea production process. Therefore, this study aims to assess the techno-economic aspects of a small-scale power-to-green urea plant based on PV electricity situated in Nusa Tenggara Barat that projects green urea price in 2019, 2030, and 2050 while also taking into account clean development mechanism in its revenue stream.

1.1. System description
The concept of power-to-green urea is an extension of the power-to-x concept in which excess or available renewable electricity is transformed into a specific end product; it could range from gaseous hydrogen, liquid fuels like methanol, or reverted back into power if need be [9]. The proposed power-to-green urea plant is then made up of four sub-systems as follows; PV-electrolysis unit, carbon capture amine and air separation unit, Haber-Bosch ammonia synthesis unit, and a urea synthesis unit.

1.1.1. PV-electrolysis. Solar energy together with water are available at all location especially in an archipelagic and tropical country like Indonesia. The average Indonesian daily horizontal irradiation (DHI) is 4.4-4.8 kWh/m² and on certain locations even as high as 6 kWh/m² [10]. Situated in Nusa Tenggara Barat, the hypothetical plant will experience a DHI of 6 kWh/m². The combination of PV array and an electrolyzer is then referred as PV-electrolysis, this system is also coupled with battery to accommodate intermittency, allowing continuous hydrogen production amongst silicone-based panels, monocrystalline silicone (m-si) has been found to outperform other of the same class in tropical Indonesian climate [11]. Looking forward PV investment costs will decrease significantly as it has already had in recent years [12]. The same trend follows with Li-ion battery; the choice of Li-ion is due to significant cost reduction in the future and also its current available size [13].

Commercial electrolysis of water employs either alkaline electrolyzer (AEL) or proton exchange membrane (PEM); the former being more established technologically than the latter [14]. In an intermittent system where electricity is highly variable, PEM is better over AEL system due to its resilience to dynamic operation; however, this is unnecessary as the plant will run continuously. Thus AEL is chosen as the electrolyzer of choice for the study.

1.1.2. Carbon capture and air separation. In this study, water electrolysis is utilized to produce carbon-free hydrogen, it is then necessary to source the gas through different means namely carbon capture using monoethanolamine (MEA). The choice of post-combustion capture using MEA is opted to its maturity, cost, and energy consumption over other promised contender being membrane separation [15].

The utilization of MEA in carbon dioxide capture process is considered as chemical absorption. The global reaction along the capture process and constants is available in Aspen Plus process simulator databank [16][17]. Due to the size of the plant, a pressure swing adsorption unit is combined with carbon capture system separating the nitrogen from clean gas produced from the top absorber column [18].

1.1.3. Ammonia and urea synthesis. Ammonia is a reactant for urea synthesis and is produced through a century old Haber-Bosch process. The process involves passing gaseous nitrogen and hydrogen of high purity through an adiabatic fixed-bed reactor with an iron catalyst; the reaction is highly exothermic needing multiple-bed with quenching in between by fresh feed [19].
Urea is produced through a two-step reaction involving ammonia and carbon dioxide forming ammonium carbamate then its dissociation into urea and water. State-of-the-art urea synthesis licensed by Stamicarbon could yield around 99% of the input carbon dioxide after recycling. A simulation model for urea synthesis is available in Aspen Plus Case Example Directory and is based on Stamicarbon licensed process [20]. The ammonium carbamate dissociation step is endothermic; however, no heat is required as ammonium carbamate formation is exothermic, thus sustaining the reaction on its own.

2. Method
The analysis consists of two major steps; process simulation of power-to-green urea plant followed by cost estimation and cash flow analysis. Aspen Plus V11 process simulator is employed to perform process simulation and cash flow analysis is conducted by Microsoft Excel.

2.1. Process simulation
As design basis, the capacity of small-scale urea plant is 13000 MT/year. Aspen Plus process simulator is used to simulate carbon capture using amine, ammonia synthesis, and urea synthesis. Process flow diagram for PV-electrolysis, carbon capture using amine, ammonia synthesis, and urea synthesis are presented in Figure 1-4. Feed for the aforementioned processes in figure 1-4 in order are water, flue gas, nitrogen and hydrogen, and ammonia and carbon dioxide; whilst its product are hydrogen and oxygen, carbon dioxide and nitrogen, ammonia, and urea, respectively.

Tool for modelling AEL in Aspen Plus is not available, thus, the CALCULATOR block feature together with its built-in Fortran script writer is used to model the reaction involved inside an electrolyzer. Equations that model the phenomenon inside an AEL was adopted from [21], the result of the model shows water to hydrogen conversion and its corresponding required electricity input. Physical characteristics of AEL module such as its active area and current density is based on operating data from by [22]. The equation to calculate energy input from PV-battery system to the AEL is presented in equation 1, with \( V_{stack} \) being voltage in volts of a stack (V), \( N \) being number of stacks, \( I \) being current density in ampere (A), and \( W_{elec} \) being power input in Watts (W). \( V_{stack} \) is a function of pressure and temperature of the system and for this study a constant 80\(^\circ\) C and 7 bar is chosen as operating condition.

\[
W_{elec} = V_{stack} \times I \times N
\]  

(1)

The PV array is designed in order to capture electricity required for a continuous operation of the plant with a supporting Li-ion battery. Capacity factor (CF) of PV array in Nusa Tenggara Barat could reach 0.25, with equation 2 rated power of the PV array is calculated [8]. Battery size \( (B_{size}) \) is the product of electricity consumption \( (W_{elec}) \) and operating hour of electrolyzer without available irradiation \( (h_{nosun}) \), giving the battery size through equation 3 [23].

\[
W_{rated} = \frac{W_{elec}}{CF}
\]

\[
B_{size} = W_{elec} \times h_{nosun}
\]

(2)  
(3)

Carbon dioxide capture from flue gas originating from Batu Hijau Coal Power Plant is simulated with ELEC-NRTL fluid package to make up for ionic interaction and non-idealities in liquid phase [24]. RadFrac block is used to model both the absorber and desorber with operating condition adapted from the work of Zhang & Chen [16] which has been optimized to recover 99% of carbon dioxide from the flue gas. It is assumed that the composition of Batu Hijau flue gas is similar to flue gas composition delivered by Arachchige & Melaaen [24] with an additional assumption of neglecting hydrogen sulfide composition. A black-box PSA is retrofitted into the flowsheet taking in clean gas and purifying nitrogen for ammonia synthesis purpose [19].
Ammonia synthesis uses the NRTL fluid package due to the non-idealities involved in the mixture. The three-bed fixed reactor is modelled with the R-PLUG block in Aspen Plus process simulator and is an adaptation from an actual plant in China; operating condition of reactor inlet is at 305°C and 140 bar with a single pass mole conversion of 25% which agrees with condition available in [19]. Rate equation for industrial iron catalyst is available and is presented in equation 4 [19].

\[
r_{NH_3} = \frac{2f}{\rho_{cat}} \left( k_1 P_{N_2} \frac{P_{H_2}^{1.5}}{P_{NH_3}} - k_{-1} \frac{P_{NH_3}}{P_{H_2}^{1.5}} \right)
\]

The final simulation for urea is obtained from Aspen Plus Sample Case Directory [20] a sample simulation for a large-scale Stamicarbon urea synthesis given by Aspen Plus is used as a starting point for the simulation. A modification towards operating condition and flowsheet is carried out to match industrial operating condition [25]. The process starts at the high-pressure carbamate condenser (HPCC), reactants are converted into ammonium carbamate; the conversion is set using the design specification feature on Aspen Plus process simulator as to maintain the outlet temperature of urea synthesis reactor at 185°C. The resulting urea solution is sent into the stripper to be liberated using fresh carbon dioxide incoming from the carbon capture unit.

**Figure 1.** Alkaline electrolyzer process flow sheet.

**Figure 2.** Carbon capture with pressure swing adsorption process flow sheet.
2.2. Technical Analysis
Evaluation of plant efficiency (LHV) will only include PV-electrolysis to ammonia synthesis; a reduction in system boundary is made due to urea being a non-fuel end product. However, energy consumption will include the whole system boundary as previously addressed.

2.2.1. System efficiency. The power-to-ammonia efficiency ($\eta_{\text{system}}$) is defined as shown in equation 5 and its variables in equation 6-8 [21][23][26].

$$\eta_{\text{system}} = (\eta_{\text{PV}} \times \eta_{\text{AEL}} \times \eta_{\text{NH}_3}) \times 100\%$$  \hspace{1cm} (5)

$$\eta_{\text{PV}} = \frac{E_{\text{elec}}}{A \times \text{GHI}}$$  \hspace{1cm} (6)

$$\eta_{\text{AEL}} = \frac{E_{\text{elec}}}{M_{\text{H}_2} \times \text{LHV}_{\text{H}_2}}$$  \hspace{1cm} (7)

$$\eta_{\text{NH}_3} = \frac{E_{\text{elec}}}{M_{\text{NH}_3} \times \text{LHV}_{\text{NH}_3}}$$  \hspace{1cm} (8)

Where $\eta$ is efficiency (%), $M$ is the mass flow rate (kg/h), $\text{LHV}$ is the lower heating value (kWh/kg), $ED$ is energy demand (kWh/kg), $E$ is energy used in one-hour interval (kWh), $A$ is solar array area (m$^2$), and GHI is global horizontal irradiation (kWh/m$^2$) respectively.

2.2.2. Specific energy consumption. The energy consumption of urea production ($ED_{\text{urea}}$) is defined as shown in equation 9 [26].

Figure 3. Ammonia synthesis process flow sheet.

Figure 4. Urea synthesis process flow sheet.
\[ ED_{\text{urea}} = \frac{E_{\text{sunlight}} + E_{u-NH_3} + E_{u-\text{urea}}}{M_{\text{urea}}} \]  

Where \( E_{\text{sun}} \) is the energy input into PV in an hour (kWh), \( E_{u-NH_3} \) is the energy input for ammonia synthesis in an hour (kWh), and \( E_{u-\text{urea}} \) is the energy input for urea synthesis in an hour (kWh). The utility for ammonia synthesis has include power to generate nitrogen, refrigeration, load, compression, and heating duties.

2.3. Economic assessment
The determination of urea price (USD/MT urea) is evaluated through cash flow analysis. Determination of CAPEX of carbon capture, ammonia synthesis, and urea synthesis is estimated based on [27] using modular and Guthrie method; this method has an uncertainty of ±20%. As for pressure swing adsorption, the usage of sixth-tenth rule [27] on CAPEX data provided by [8]; the method is employed because it is a black-box model. PV base CAPEX is given by [28] and is projected using learning rate of 37%, electrolyzer base CAPEX is given by [29] and projected with learning rate of 55.8%, and battery CAPEX is acquired through projection by [13].

Urea price is determined using 4 schemes; Scheme 1 determines urea price without CDM and 2 with CDM, Scheme 3 determines the price of urea without CDM and projected investment cost for battery, PV, and electrolyzer in 2030 (3a) and 2050 (3b), and Scheme 4 which is a combination of Scheme 2 and 3 in 2030 (4a) and in 2050 (4b). The plant will enjoy additional revenue stream from oxygen, nitrogen, and CDM with a flat price of 50, 177, and 30 USD/MT, respectively throughout its 25 years lifetime. CAPEX investment will be fulfilled through bank-loan (70%) and hypothetical investor equity (30%). Yearly loan interest will be in accordance to Bank Indonesia rate in 2019 at 6%, income tax will be set at 25%, cost of equity is calculated and yield result of 9.25%, and the internal rate of return of the plant is set above the calculated weighted average cost of capital (WACC) at 10%. The resulting price will be compared to a large-scaled commercial urea price according to [30] and a hypothetical small-scaled natural gas urea scaled through sixth-tenth rule with data acquired from [31]. CAPEX and OPEX data for each unit involved in the plant is presented in Table 1.

| Technology          | Year | PV (USD/kW) | Battery (USD/kWh) | AEL (USD/kW) | Carbon capture (USD/kW) | Ammonia synthesis (USD/kW) | Urea Synthesis (USD/kW) |
|---------------------|------|-------------|-------------------|--------------|------------------------|---------------------------|-------------------------|
| 2019                |      | 1250        | 376               | 840          |                        |                           |                         |
| 2030                |      | 797         | 306               | 348          |                        | Guthrie CAPEX estimation |                         |
| 2050                |      | 521         | 268               | 158          |                        |                           |                         |
| OPEX (USD/y)        |      | 1%          | 2% CAPEX          | 2% CAPEX     | 7% CAPEX               | 1.5% CAPEX                | 1.5% CAPEX              |
| Ref.                |      | [28][32]    | [13][33]          | [29]         | [34]                   | [35]                      | [35]                    |

3. Results and discussion
3.1. Energy system analysis
The flow of energy is presented in Sankey Diagram (Figure 6). The flow of energy starts from PV to the final urea production; each process involved have their given efficiency as given by equation 5 through 8. The energy consumption for urea production can also be extracted from the Sankey Diagram given.
Efficiency of PV, AEL, and ammonia synthesis unit are 19.4, 63.35, and 64%, respectively with its overall efficiency of 7.9%. Comparing with a conventional ammonia production with efficiency of 42-48%, the system does fall behind. It is to be noted that conventional ammonia is only comprised of two process units in order to procure ammonia; whilst power-to-ammonia has an additional power source namely photovoltaic; thus, in actuality the process is energy-wise competitive when only hydrogen production is compared. The efficiency of hydrogen production through steam methane reforming and electrolysis is comparable with the former having an efficiency of 65-75% and the latter of 45-67% with lower heating value as its basis. Although power-to-ammonia lacks in round-trip efficiency; the green and unlimited aspect sunlight as its energy source is its edge over conventional ammonia production process.

The energy consumption of urea production is 109 GJ/MT urea as calculated using equation 17. Conventional urea from natural gas has an energy consumption of about 21.6 GJ/MT urea; this translates to 500% increase in energy consumption to produce an equal amount of urea. Similar to its conventional counterpart, the hydrogen production process with the proposed power-to-green urea consumes 91% of total energy and leaving 9% for utilities and also carbon dioxide capture; thus, focusing future studies on lowering energy consumption for the process should aim its focus on the hydrogen production section.

### 3.2. Economic analysis

CAPEX is evaluated through benchmarking with a previous feasibility study due to no power-to-green urea plant at the present. A CAPEX breakdown is presented in Table 2. Throughout the cost breakdown, battery and PV dominates the share of CAPEX although reduction of cost is present in year beyond 2019. Both of the component still dominates around 50% of the overall CAPEX up to 2050, the reduction of these components is then a determining in realizing proposed design of a small-scaled green urea production plant. Another dominant CAPEX contributor is the ammonia synthesis unit which never fall short from 21% of CAPEX share as its cost is not projected. As another major contributor towards total CAPEX, the ammonia synthesis unit should be taken notice in future studies; perhaps taking into account its cost reduction in 2030 and 2050.

Cash flow analysis of Scheme 1-4 is presented in Figure 8. A significant reduction of green urea price from the base year is not present earlier in 2030; however, in 2050 a 27% reduction in price occurs. The addition of revenue through CDM initiative has also not able to reduce green urea price, only enabling a reduction of at most 1.2%. Throughout the analysis, there is no available scheme and year in which a small-scaled power-to-green urea can compete with a large-scaled commercial urea, this also applies to a hypothetical small-scaled natural gas-based urea. Although green urea price does not decrease significantly throughout the study, its hypothetical counterpart rise in price is a subject of interest. In 2019, a hypothetical small-scaled plant with an equal output as the design basis experience a 200% increase in price by 2050. Through this observation, conventional urea is volatile due to increase in incoming rise of gas price, but green urea does not follow the same trend due to its feedstock being water and electricity. Difference in price of conventional urea produced from a large and small-scaled also differs greatly; it seems that due to economies of scale.
Figure 5. Power-to-green urea Sankey diagram.

Table 2. CAPEX share and projection of hypothetical power-to-green urea plant.

| Year   | Total Investment (M USD) | Share (%) |
|--------|--------------------------|-----------|
| 2019   | 195                      |           |
| 2030   | 171                      |           |
| 2050   | 146                      |           |

| Component            | Share (%) |
|----------------------|-----------|
| Ammonia unit         | 21        |
| Urea unit            | 8         |
| PV                   | 20        |
| Battery              | 34        |
| Carbon capture unit  | 4         |
| Offsite facilities   | 4         |

Figure 6. Urea price comparison with 4 proposed schemes.

4. Conclusion
Through the energy and mass balance of the plant, usage of equation 5-9 for technical assessment and the execution of cash flow analysis the results are obtained as follows, efficiency and specific energy consumption are 7.9% and 109 GJ/MT urea with lower heating value as basis; and green urea price from Scheme 1-4 are 2342, 2320, 2026 and 1704, and 2004 and 1682 USD/MT, respectively. From an energy perspective, the power-to-green urea is less efficient than its conventional counterpart and leads to a 500% increase in urea production energy consumption. From an economic perspective, power-to-green urea could not compete even with the upcoming cost reduction of PV-electrolysis and battery in 2030 and 2050. The CDM initiative is not enough to reduce green urea prices, resulting only a 1.2% price reduction. It is then to be noted that small-scaled power-to-green urea is not economically feasible, but for remote areas without gas reserves, the concept is still relevant; considering easily procured raw material being water, resistant to spikes in natural gas prices, while also being environmentally green.

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