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Supplementary Information

Assessing the Feasibility of Gray, Blue, and Green Ammonia Production in Indonesia: A Techno-Economic and Environmental Perspective

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A. Definitions

a. Capacity factor
Plant's actual output or throughput over a period of time compared to its full capacity. The average capacity factor for an ammonia plant is 90%.

b. Discount rate
Rate of interest that is applied to the future cash flows of an investment to calculate its present value. In this case, the discount rate is assumed to be 8%.

c. LHV of NG
Thermal energy produced by the combustion of natural gas with energy losses consideration due to the vaporization of water. In this case, the LHV of NG is assumed to be 46.5 GJ/ton.

d. MVC
Mechanical vapor compression is a method used to purify electrolyzer's feed water.

e. Balance of plant
Supporting components and auxiliary systems, including air system, flare system, drain system, interconnecting, and buildings.

f. Amortization
The cost for repayment of debt through periodic installments over a period of time. In this case, amortization occurs only for green ammonia due to the requirement to replace the electrolyzer's stack every 6 and 10 years for PEM and alkaline electrolyzers, respectively.

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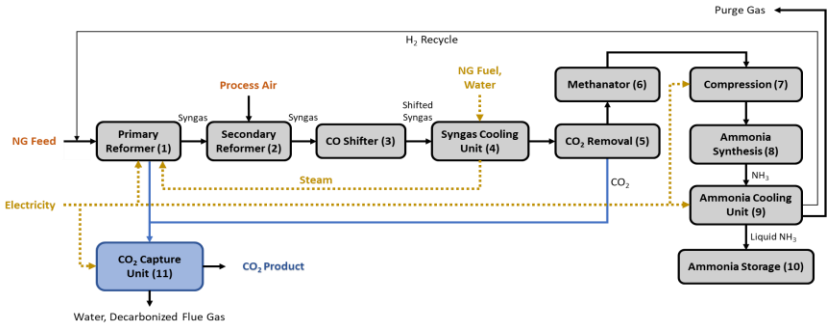
B. Graphical User Interface of Spreadsheet-Based Decision Support System

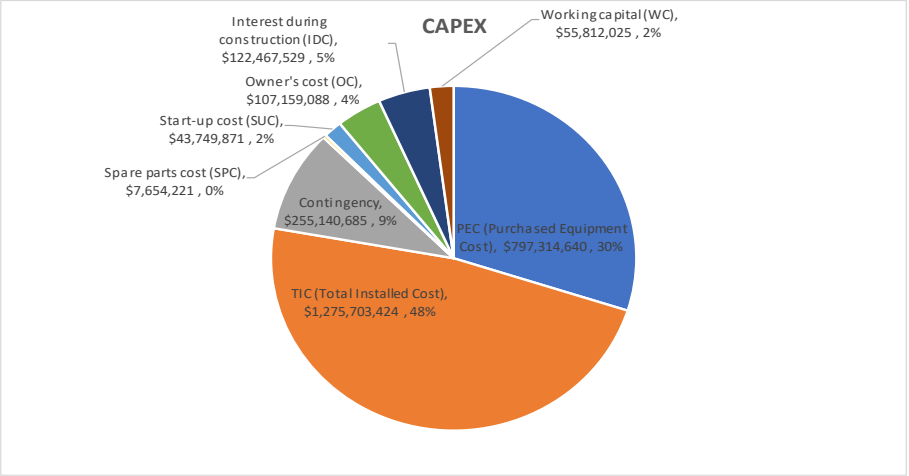
COLOR DICTIONARY
Insert a number
Choose from the dropdown
Calculation result

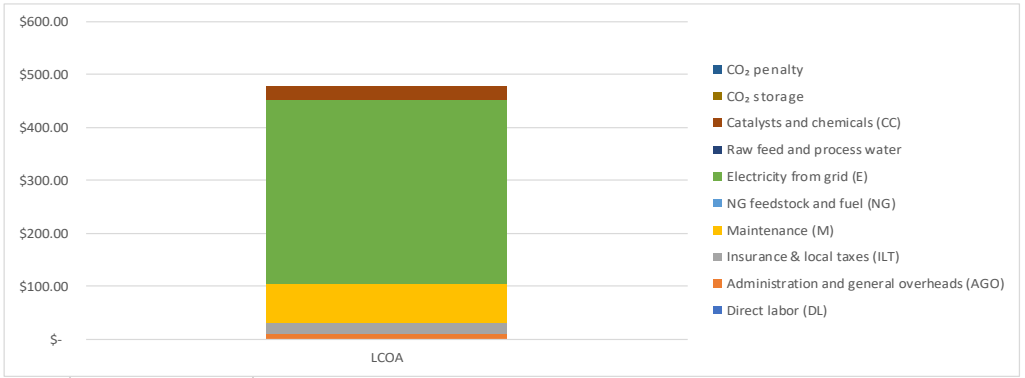
INPUT				
Ammonia type	Green			
Electrolyzer	Alkaline			
Green electricity source	Hydro			
	-			
Annual plant capacity		730,000	ton NH_3/year	
Capacity factor		90	%	
Discount rate (DR)		8.0	%	IEAGHG, 2017
LHV of NG		46.5	GJ/ton	IEAGHG, 2017
Natural gas (NG) cost		6.0	$/GJ (LHV)	ESDM
Raw water cost		0.4	$/m³	
Grid electricity cost options	Manual input			
Grid electricity cost suggested		45.0	$/MWh	Perpres
Grid electricity cost manual input		37.6	$/MWh	
CO_2 capture from boiler cost		70.0	$/t CO_2 captured	Raksajati
CO_2 storage cost		10.8	$/t CO_2 stored	IEAGHG, 2017
CO_2 penalty cost		90.0	$/t CO_2 emitted	
Individual average salary (AS)		9,730	$/person	
Energy setting (see Table 5)	Following suggestion			
Electricity suggested		33.38784	GJ/ ton NH_3	
Electricity manual input	Do not enter		GJ/ ton NH_3	
NG feedstock suggested		0	GJ/ ton NH_3	
NG feedstock manual input	Do not enter		GJ/ ton NH_3	
NG fuel suggested		0	GJ/ ton NH_3	
NG fuel manual input	Do not enter		GJ/ ton NH_3	

Variables	Value	Unit		
Electricity	21,935,811	GJ/yr		
NG feed	-	GJ/yr		
NG fuel	-	GJ/yr		
TOTAL ENERGY CONSUMPTION	**21,935,811**	**GJ/yr**		
Raw feed and process water	1,771,929	m³/yr		
CO_2e produced from onsite reformer	-	ton CO_2e/yr	-	-
CO_2e produced from onsite boiler	-	ton CO_2e/yr	-	-
CO_2e captured from onsite reformer	-	ton CO_2e/yr	-	
CO_2e captured from onsite boiler	-	ton CO_2e/yr	-	
CO_2e stored onsite	-	ton CO_2e/yr		
CO_2e released	-	ton CO_2e/yr		
Number of labor (NL)	55			



CAPITAL COST (CAPEX)		**Cost**
HB reactor	$	197,889,120
SMR	$	-
Electrolyzer modules	$	370,666,667
MVC	$	89,333,333
ASU	$	139,425,520
CO_2 capture unit	$	-
CO_2 compression unit	$	-
PEC (Purchased Equipment Cost)	**$**	**797,314,640**
Utilities and BoP	$	478,388,784
TIC (Total Installed Cost)	**$**	**1,275,703,424**
Contingency	$	255,140,685
TPC (Total Plant Cost)	**$**	**1,530,844,109**
Spare parts cost (SPC)	$	7,654,221
Start-up cost (SUC)	$	43,749,871
Owner's cost (OC)	$	107,159,088
Interest during construction (IDC)	$	122,467,529
Working capital (WC)	$	55,812,025
TCR (Total Capital Requirement)	**$**	**1,867,686,842**
OPERATIONAL COST (OPEX)		
Direct labor (DL)	$	535,150
Maintenance (M)	$	45,925,323
Insurance & local taxes (ILT)	$	15,308,441
Administration and general overheads (AGO)	$	5,671,584
Amortization (A)	$	16,680,000
Subtotal fixed operational cost (FOC)	**$**	**84,120,498**
NG feedstock and fuel (NG)	$	-
Electricity from grid (E)	$	229,107,358
Raw feed and process water	$	708,772
Catalysts and chemicals (CC)	$	16,047,997
CO_2 capture	$	-
CO_2 storage	$	-
CO_2 penalty	$	-
Subtotal variable operational cost (VOC)	**$**	**245,864,126**
Total Operational Cost (TOC)	**$**	**329,984,624**
LCOA	**$**	**502**





C. Parameters and Formula for Calculating LCOA

The details of LCOA calculation starting from the energy consumptions, emissions, capital cost, and operational cost for each scenario are provided in **Table S1, S2, S3, and S4**. These calculations are adapted from IEAGHG (2017) and Rivarolo *et al.* (2019).

Table S1. Major installed cost components for gray and blue ammonia production.

Unit Operation	Gray	Blue
Haber-Bosch (HB) Reactor	$\frac{\$208,427,670}{1,350\ (\text{tpd})} \times \text{C (tpd)}$	$\frac{\$211,434,097}{1,350\ (\text{tpd})} \times \text{C (tpd)}$
Steam Methane Reforming (SMR)	$\frac{\$304,248,487}{1,350\ (\text{tpd})} \times \text{C (tpd)}$	$\frac{\$308,564,977}{1,350\ (\text{tpd})} \times \text{C (tpd)}$
Utilities and Balance of Plant (BoP)	$\frac{\$55,774,000}{1,350\ (\text{tpd})} \times \text{C (tpd)}$	$\frac{\$59,696,000}{1,350\ (\text{tpd})} \times \text{C (tpd)}$
CO_2 Capture Unit	-	$\frac{\$48,360,000}{1,350\ (\text{tpd})} \times \text{C (tpd)}$
CO_2 Compression Unit	-	$\frac{\$10,400,000}{1,350\ (\text{tpd})} \times \text{C (tpd)}$

Note: The installed cost of each major component is approximated to be proportional to the production capacity (C). We have used a reference capacity of 1350 tons ammonia per day (tpd) (IEAGHG, 2017).

Table S2. Major installed cost components for green ammonia production.

Unit Operation	**Alkaline**	**PEM**
Mechanical Vapor Compression (MVC)[a]	$\text{MVC} = \frac{\$13{,}400{,}000}{300\ (\text{tpd})} \times \text{C (tpd)}$	$\text{MVC} = \frac{\$11{,}960{,}000}{300\ (\text{tpd})} \times \text{C (tpd)}$
Electrolyzer Modules (EM)[a]	$\text{EM} = \frac{\$139{,}000{,}000}{300\ (\text{tpd})} \times \text{C (tpd)}$	$\text{EM} = \frac{\$232{,}850{,}000}{300\ (\text{tpd})} \times \text{C (tpd)}$
Air Separation Unit (ASU)[b]	$\text{ASU} = \$1.04 \times 10^6 \times \left(\frac{0.1426}{2.5} \times \text{C (tpd)} + 19.983\right)$	
Haber-Bosch (HB) Reactor[b]	$\text{HB} = \$1.04 \times 10^6 \times \left(\frac{0.2023}{2.5} \times \text{C (tpd)} + 28.438\right)$	
Purchased Equipment Cost (PEC)[b]	$\text{PEC} = \text{MVC} + \text{EM} + \text{ASU} + \text{HB}$	
Utilities and Balance of Plant (BoP)[b]	$\text{BoP} = 0.6 \times \text{PEC}$	

[a] The installed costs of MVC and EM are approximated to be proportional to the production capacity (C) of 300 tons of ammonia per day (tpd), using Nosherwani and Neto (2021) as a reference. [b] The costs of ASU, HB reactor, and BoP are calculated based on data provided by Rivarolo *et al.* (2019).

Table S3. Summary of total capital cost requirement (IEAGHG, 2017).

Component	Formula	Description
Total Plant Cost (TPC)	$\mathrm{TPC} = 120\% \times \mathrm{TIC}$	Estimated contingency 20%.
Spare Parts Cost (SPC)	$\mathrm{SPC} = 0.5\% \times \mathrm{TPC}$	About 0.5% of total plant cost.
Start-up Cost (SUC)	$\mathrm{SUC} = (2\% \times \mathrm{TPC}) + (15\% \times \mathrm{M}) + \frac{1}{12} \times (25\% \times \mathrm{NG} + 3 \times \mathrm{DL} + \mathrm{CC} + 25\% \times \mathrm{E})$	Modified start-up cost from IEAGHG (2017) to account for electricity usage (used for green ammonia analysis), which comprised of: (i) 2% of total plant cost (TPC), (ii) 15% of maintenance cost (M), and (iii) one month usage of natural gas cost (NG) at 25% capacity testing, 3 months direct labor cost (DL), one month of chemical and catalyst cost (CC), one month usage of electricity cost (NG) at 25% capacity testing. All component costs are based on annual cost.
Owner's Cost (OC)	$\mathrm{OC} = 7\% \times \mathrm{TPC}$	Assumed to be 7% of the TPC. Owner's cost covers the expenditure related to the feasibility studies, land surveys, land purchase, construction or improvement to roads and railways, water supply, and other physical infrastructures.
Interest during Construction (IDC)	$\mathrm{IDC} = \mathrm{DR} \times \mathrm{TPC}$	Interest rate assumed to be equal to discount rate (DR).
Working Capital (WC)	*Gray and blue* $\mathrm{WC} = \frac{\mathrm{NG} + \mathrm{CC}}{12}$ *Green* $\mathrm{WC} = 7\% \times \mathrm{PEC}$	Includes inventories of fuel and chemicals for one month. Assumed to be 7% of the total purchased equipment cost (PEC) (Rivarolo *et al.* 2019)
Total Capital Cost Requirement (TCR)	$\mathrm{TCR} = \mathrm{TPC} + \mathrm{SPC} + \mathrm{SUC} + \mathrm{OC} + \mathrm{IDC} + \mathrm{WC}$	Total capital cost is the summation of all the cost components listed above.

Table S4. Components of the fixed operational cost.

Component	Formula
Direct Labor (DL)[a]	NL × AS
Maintenance (M)	1.5% × TPC (Gray and blue ammonia)[a]
	3% × TPC (Green ammonia)[b]
Insurance and Local Taxes (ILT) [a]	1% × TPC
Administration and General Overheads (AGO) [a]	30% x (DL + 40% × M)
Amortization (A)[c]	$\frac{45\% \times EM}{EML}$ (Green ammonia)
Fixed Operation Cost (FOC)	$FOC = DL + M + AGO + ILT + A$

[a] IEAGHG (2017) where NL is number of direct laborers and AS is average salary, [b] Dias *et al.* (2020), [c] Used only for green ammonia calculation. The electrolyzer module cost (EM) is amortized based on the electrolyzer module lifetime (EML). The EML for alkaline electrolyzers and PEM electrolyzers is 10 years and 6 years, respectively (IRENA, 2020).

Table S5. The amount of natural gas (NG) feedstock, natural gas fuel, electricity, and raw water needed for each of the ammonia production scenarios.

Parameters	Gray	Blue	Green (Alkaline)	Green (PEM)
NG Feedstock (ton NG/ton NH_3)	0.57[a]	0.57[a]	0	0
NG Fuel (ton NG/ton NH_3)	0.22[a]	0.22[a]	0	0
Electricity (MWh/ton NH_3)	0.186[a]	0.365[a]	9.274[b]	9.869[c]
Raw Feed and Process Water (m^3/ton NH_3)	0.393[a]	0.073[a]	2.697[c]	2.697[c]
Chemicals and Catalysts ($/ton NH_3)	$\frac{\$1,248,000}{1,350\ (tpd)} \times C\ (tpd)$[d]	$\frac{\$1,248,000}{1,350\ (tpd)} \times C\ (tpd)$[d]	$\frac{40\% \times \$1,248,000}{1,350\ (tpd)} \times C + 1\% \times TPC$[e]	$\frac{40\% \times \$1,248,000}{1,350\ (tpd)} \times C$[e]

[a] adapted from IEAGHG (2017), [b] calculated from Guerra *et al.* (2020) and IRENA (2020), [c] adapted from Guerra *et al.* (2020), [d] proportionally calculated from IEAGHG (2017), [e] proportionally calculated from IEAGHG (2017) with assumption of 40% gray's chemicals and catalysts are for Haber-Bosch (HB) reactor and additional 1% of TPC is accounted for alkaline chemicals.

D. LCOA Results

Table S6. LCOA Calculation Details

Scenario	**1**	**2**	**3-A**	**3-B**	**3-C**	**3-D**
Ammonia type	Gray	Blue	Green	Green	Green	Green
Electricity source	Natural gas	Natural gas	Grid	Grid	Grid	Grid
Green electricity source	None	None	Hydro	Geothermal	Hydro	Geothermal
Grid electricity cost ($/MWh)	0	0	45	60	45	60
Electrolyzer	-	-	Alkaline	Alkaline	PEM	PEM
Electricity (GJ/ton NH_3)	0.67	1.32	33.38784	33.38784	35.5284	35.5284
NG feedstock (GJ/ton NH_3)	26.51	26.51	0	0	0	0
NG fuel (GJ/ton NH_3)	10.23	10.23	0	0	0	0
Electricity (GJ/yr)	439,927	867,634	21,935,811	21,935,811	23,342,159	23,342,159
NG Feed (GJ/yr)	17,413,785	17,413,785	-	-	-	-
NG Fuel (GJ/yr)	6,721,110	6,721,110	-	-	-	-
TOTAL ENERGY CONSUMPTION (GJ/yr)	24,574,822	25,002,529	21,935,811	21,935,811	23,342,159	23,342,159
Raw water (m^3/yr)	258,128	47,888	1,771,929	1,771,929	1,771,929	1,771,929
CO_2e produced from onsite reformer (ton CO_2e/yr)	997,810	997,810	-	-	-	-
CO_2 produced from onsite boiler (ton CO_2e/yr)	794,875	842,351	-	-	-	-
CO_2e captured from onsite reformer (ton CO_2e/yr)	-	898,029	-	-	-	-
CO_2e captured from onsite boiler (ton CO_2e/yr)	-	758,115.55	-	-	-	-
CO_2e stored onsite (ton CO_2e/yr)	-	1,656,144	-	-	-	-
CO_2e released (ton CO_2e/yr)	1,792,685	184,016	-	-	-	-

Number of labor	66	71	55	55	55	55
CAPITAL COST (CAPEX)						
HB reactor	$308,775,400	$313,235,700	$197,889,120	$197,889,120	$197,889,120	$197,889,120
SMR	$450,738,500	$457,133,300	-	-	-	-
Electrolyzer modules	-	-	$926,666,667	$926,666,667	$1,552,333,333	$1,552,333,333
MVC	-	-	$89,333,333	$89,333,333	$79,733,333	$79,733,333
ASU	-	-	$139,425,520	$139,425,520	$139,425,520	$139,425,520
CO_2 capture unit	-	$71,644,444	-	-	-	-
CO_2 compression unit	-	$15,407,407	-	-	-	-
PEC (Purchased Equipment Cost)	$759,513,900	$857,420,852	$1,353,314,640	$1,353,314,640	$1,969,381,307	$1,969,381,307
Utilities and BoP	$82,628,148	$88,438,519	$811,988,784	$811,988,784	$1,181,628,784	$1,181,628,784
TIC (Total Installed Cost)	$842,142,048	$945,859,370	$2,165,303,424	$2,165,303,424	$3,151,010,091	$3,151,010,091
Contingency	$168,428,410	$189,171,874	$433,060,685	$433,060,685	$630,202,018	$630,202,018
TPC (Total Plant Cost)	$1,010,570,458	$1,135,031,244	$2,598,364,109	$2,598,364,109	$3,781,212,109	$3,781,212,109
Spare Parts Cost (SPC)	$5,052,852	$5,675,156	$12,991,821	$12,991,821	$18,906,061	$18,906,061
Start-up Cost (SUC)	$26,740,720	$29,980,631	$66,744,854	$66,744,854	$93,559,326	$93,559,326
Owner's Cost (OC)	$70,746,064	$79,452,187	$181,885,488	$181,885,488	$264,684,848	$264,684,848
Interest during Construction (IDC)	$80,852,645	$90,802,500	$207,869,129	$207,869,129	$302,496,969	$302,496,969
Working Capital (WC)	$13,806,753	$14,012,120	$151,571,240	$151,571,240	$220,570,706	$220,570,706
TCR (Total Capital Requirement)	$1,208,200,795	$1,354,953,838	$3,067,296,170	$3,067,296,170	4,681,430,018	$4,681,430,018
OPERATING COST (OPEX)						
Direct labor (DL)	$642,180	$690,830	$535,150	$535,150	$535,150	$535,150
Maintenance (M)	$15,158,557	$17,025,469	$77,950,923	$77,950,923	$113,436,363	$113,436,363
Insurance & local Taxes (ILT)	$10,105,705	$11,350,312	$25,983,641	$25,983,641	$37,812,121	$37,812,121
Administration and general overheads (AGO)	$2,011,681	$2,250,305	$9,514,656	$9,514,656	$13,772,909	$13,772,909
Amortization (A)	-	-	$41,700,000	$41,700,000	$116,425,000	$116,425,000

Subtotal fixed operating cost	$32,437,208	$36,178,357	$159,450,275	$159,450,275	$285,747,448	$285,747,448
NG Feedstock and fuel (NG)	$147,448,933	$150,015,175	-	-	-	-
Electricity from grid (E)	-	-	$274,197,636	$365,596,848	$291,776,985	$389,035,980
Raw water	$103,251	$19,155	$708,772	$708,772	$708,772	$708,772
Chemicals & catalysts (CC)	$1,848,889	$1,848,889	$26,723,197	$26,723,197	$739,556	$739,556
CO_2 capture	-	$53,068,088	-	-	-	-
CO_2 storage	-	$17,886,360	-	-	-	-
CO_2 penalty	$17,926,850	$1,840,160	-	-	-	-
Subtotal variable operating cost	$167,327,923	$224,677,828	$301,629,604	$393,028,816	$293,225,312	$390,484,307
Total Operating Cost	$195,246,046	$255,994,744	$457,313,974	$548,713,186	$575,206,855	$672,465,850
LCOA	$297	$390	$696	$835	$876	$1,024

E. GHG Factor Calculation

The composition of flash gas produced from the steam methane reforming (SMR) unit for gray ammonia is gained from the reference Lee *et al.* (2022) as described in **Table S7**. The conversion equivalent factor to CO_2 is based on reference World Resource Institute (2023).

Table S7. Conversion calculation into CO_2 equivalent value for "CO_2 from aMDEA" stream from reference Lee et al. (2022)

	Mass (kg/kg NH_3)	**Mol fraction**	**Mass (kg/kg NH_3)**	**CO_2 equivalent factor**	**Carbon emission**	**Total carbon emission (kg CO_2e/kg NH_3)**
CO_2	1.32	0.97	1.298	1	1.298	1.403
CH_4		0.01	0.005	21	0.105	
Ar		0.01	0.012	0	0	
H_2O		0.01	0.005	0	0	

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