Comparative sustainability assessment of hydrogen supply network for hydrogen refueling stations in Korea – A techno-economic and life cycle assessment perspective

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Table S.1. Data used for calculating capital cost.

Equipments	Baseline Purchased Cost USD	Year of quote	Installation factor	Reference
Air Separation Unit (ASU)				
Heat Exchangers	641,080	2010	2.17	1
Compressors	549,000	2010	2.75	1
Drivers	316,740	2010	1.5	1
High Pressure Distillation Column	120,800	2010	13.73	1
Low Pressure Distillation Column	153,700	2010	8.20	1
Turbine	14,590	2010	6.10	1
Water Purification Unit (MVC)				
Compressor	164,050	2010	2.75	1
Driver	102,630	2010	1.5	1
Evaporator	1,235,220	2010	3.0	1
Flat Plate HX	454,940	2010	2.99	1
Flat Plate HX	1,047,740	2010	2.99	1
Ammonia Synthesis Loop				
Heat Exchangers	2,154,355	2010	2.17	1
Compressors	4,545,891	2010	2.75	1
Drivers	1,083,847	2010	1.5	1
Reactors	1,291,755	2010	2.45	1
Pumps	363,650	2010	1.6	1

Table S.2. Multiplier for calculating direct, indirect costs and capital cost breakdown.[2]

Cost distribution **Direct costs**	Multiplier
Warehouse	4% of ISBL
Site Development	9% of ISBL
Additional piping	5% of ISBL
Indirect Costs	
Portable Expenses	10% of TDC
Field Expenses	10% of TDC
Home Office & construction Fee	20% of TDC
Project Contingency	10% of TDC
Other Costs (start-up, permits, etc.)	10% of TDC
Working Capital	20% of ISBL

Table S3. Environmental indicators and definition.

Impact Category (Units per kg emission)	Definition	Relevant LCI Data
Abiotic Depletion Potential (ADP) (kg Sb eq)	Cumulative quantification of impact caused by extraction of minerals due to inputs in the system	Extraction of mineral resources
Abiotic Depletion Potential (fossil fuels) (ADPFF) (MJ)	Surplus energy (lower hating value) per extracted MJ, kg or m^3 fossil fuel, as a result of lower quality resources; unavailable for use by future generations	Extraction of fossil fuel resources
Global Warming Potential (GWP 100a) (kg CO_2 eq)	GWP potential for time horizon 100 years: Impact caused by emissions of greenhouses gases	CO_2, NO_2, CH_4, CFC_S, $HCFC_S$, CH_3BR
Ozone Layer Depletion Potential (ODP) (kg CFC-11 eq)	Thinning of ozone layer due to greenhouse gas emissions	CFC_S, $HCFC_S$, CH_3BR, Halons
Human Toxicity Potential (HTP) (1,4-dichlorobenzene eq)	Potential detrimental effect of toxic substances within the environment on human health	Human toxic substances
Fresh Water Aquatic Ecotoxicity Potential (FETP) (1,4-dichlorobenzene eq)	Potential impact of toxic substances on aquatic ecosystems	Toxic substances with a reported lethal concentration to fish
Photochemical Oxidation Potential (PCOP) (kg C_2H_4 eq)	Production of reactive chemical compounds, such as ozone, by the action of sunlight on pollutants in the air	PM10, NH_3, SO_2. NO_X, and NMVOC
Acidification Potential (ACP) (kg SO_2 eq)	Acidic compounds formation as a result of manufacturing process	SO_X
Eutrophication Potential (EP) (kg PO_4 eq)	Cumulative quantification of phosphorus compounds formation	Nitrogen and Phosphorus compounds

Table S4. Costs used for LCOH forecasting.

Parameter	2020	2025	2030	Reference
Solar PV	902	733	565	[3]
AWE Capex	903	720	588	[4–6]
AWE Opex	408	324	240	[4–6]
LCOA	0.9	0.74	0.6	Authors
HRS+CSD	5.66	5.32	5.1	Authors
Solar PV Electricity price	0.106	0.095	0.085	[7]
Grid Integration cost	0.032	0.033	0.038	[7]

Table S5. LCA results (Per 1kg H_2) according to CML-IA baseline method.

Impact category	Unit	Case 1	Case 2	Case 3
ADP	kg Sb eq	1.48E-03	1.13E-03	1.07E-03
ADPFF	MJ	7.76E+01	6.26E+01	5.18E+01
GWP	kg CO2 eq	6.81E+00	5.35E+00	4.57E+00
ODP	kg CFC-11 eq	8.10E-07	6.63E-07	5.37E-07
HTP	kg 1,4-DB eq	1.46E+01	1.12E+01	1.05E+01
FETP	kg 1,4-DB eq	1.20E+01	9.15E+00	8.74E+00
PCOP	kg C2H4 eq	1.97E+04	1.50E+04	1.43E+04
ACP	kg SO2 eq	2.38E-02	1.82E-02	1.67E-02
EP	kg PO4 eq	2.23E-03	1.53E-03	1.40E-03

Table S6. List of Ecoinvent v3.6 databases selected for LCA of studied cases.

Processes
Calendering, rigid sheets {GLO}| market for | APOS, S
Acrylonitrile-butadiene-styrene copolymer {RoW}| production | APOS, S
Tetrafluoroethylene {GLO}| market for | APOS, S
Polyphenylene sulfide {GLO}| market for | APOS, S
N-methyl-2-pyrrolidone {GLO}| market for | APOS, S
Aniline {RoW}| market for aniline | APOS, S
Purified terephthalic acid {GLO}| market for | APOS, S
Acetic anhydride {GLO}| market for acetic anhydride | APOS, S
Nitric acid, without water, in 50% solution state {RER}| market for nitric acid, without water, in 50% solution state | APOS, S
Hydrochloric acid, without water, in 30% solution state {RER}| hydrochloric acid production, from the reaction of hydrogen with chlorine | APOS, S
Zirconium oxide {GLO}| market for | APOS, S
Carbon monoxide {RoW}| market for | APOS, S
Water, deionised {RoW}| water production, deionised | APOS, S
Industrial machine, heavy, unspecified {RoW}| production | APOS, S
Plaster mixing {GLO}| market for | APOS, S
Water, decarbonised {GB}| market for water, decarbonised | APOS, S
Steel, unalloyed {GLO}| market for | APOS, S
Heat, central or small-scale, other than natural gas {GLO}| market group for | APOS, S
Heat, from steam, in chemical industry {RoW}| steam production, as energy carrier, in chemical industry | APOS, S
Water, deionised {RoW}| water production, deionised | APOS, S
Potassium hydroxide {GLO}| market for | APOS, S
Steam, in chemical industry {RoW}| production | APOS, S
Nitrogen, liquid {RoW}| air separation, cryogenic | APOS, S
Iron ore, crude ore, 63% Fe {GLO}| market for iron ore, crude ore, 63% Fe | APOS, S
Potassium hydroxide {RoW}| production | APOS, S
Aluminium oxide, metallurgical {UN-OCEANIA}| aluminium oxide production | APOS, S
Refinery gas {RoW}| refinery gas production, petroleum refinery operation | APOS, S
Compressed air, 600 kPa gauge {RoW}| market for compressed air, 600 kPa gauge | APOS, S
Electricity, low voltage {RoW}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | APOS, S
Transport, freight, lorry 7.5-16 metric ton, EURO6 {RoW}| transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, S
Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship | APOS, S

FIGURES.

CAPEX and OPEX breakdown

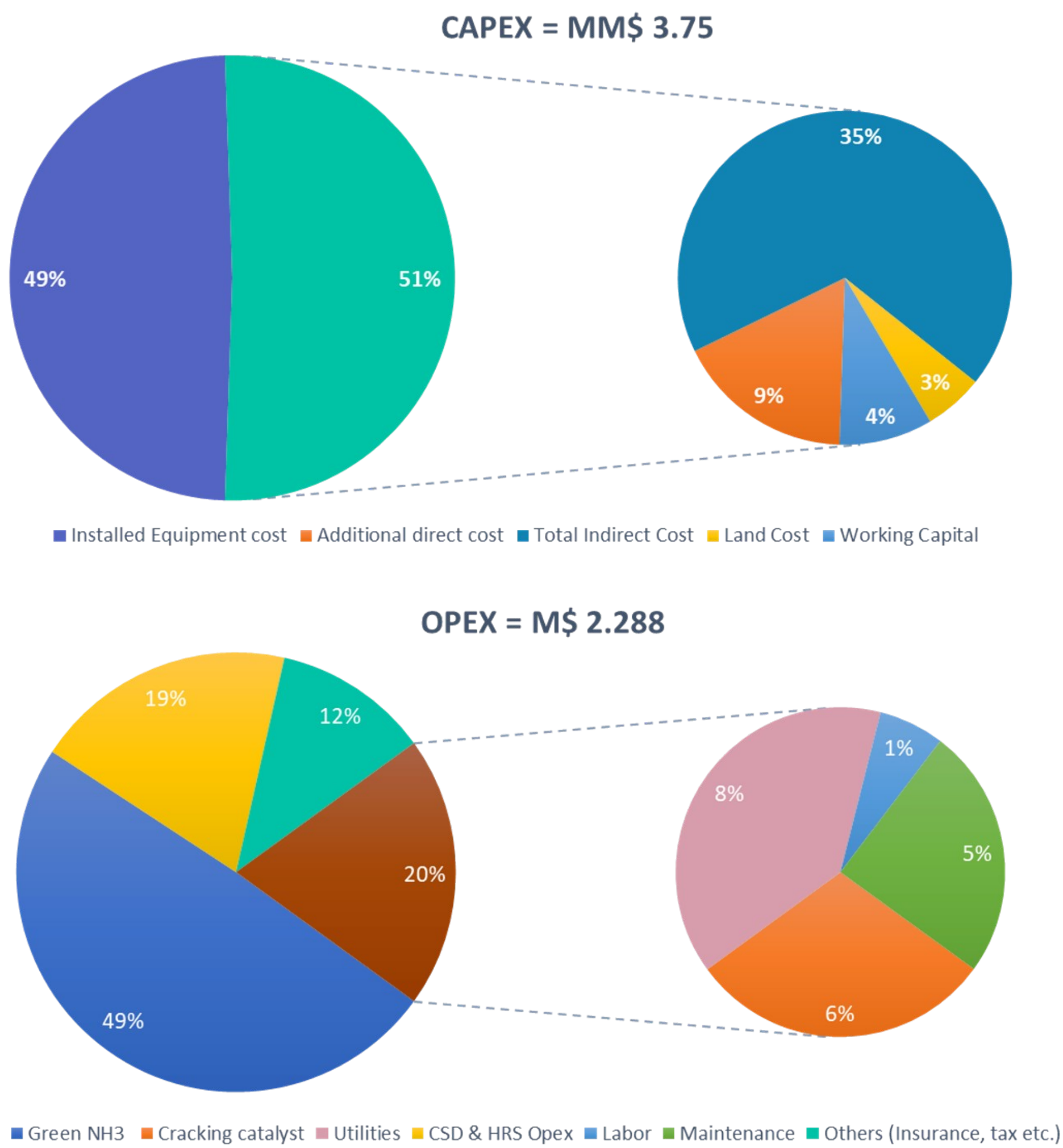

Fig.S 1. CAPEX and OPEX breakdown for Case 1.

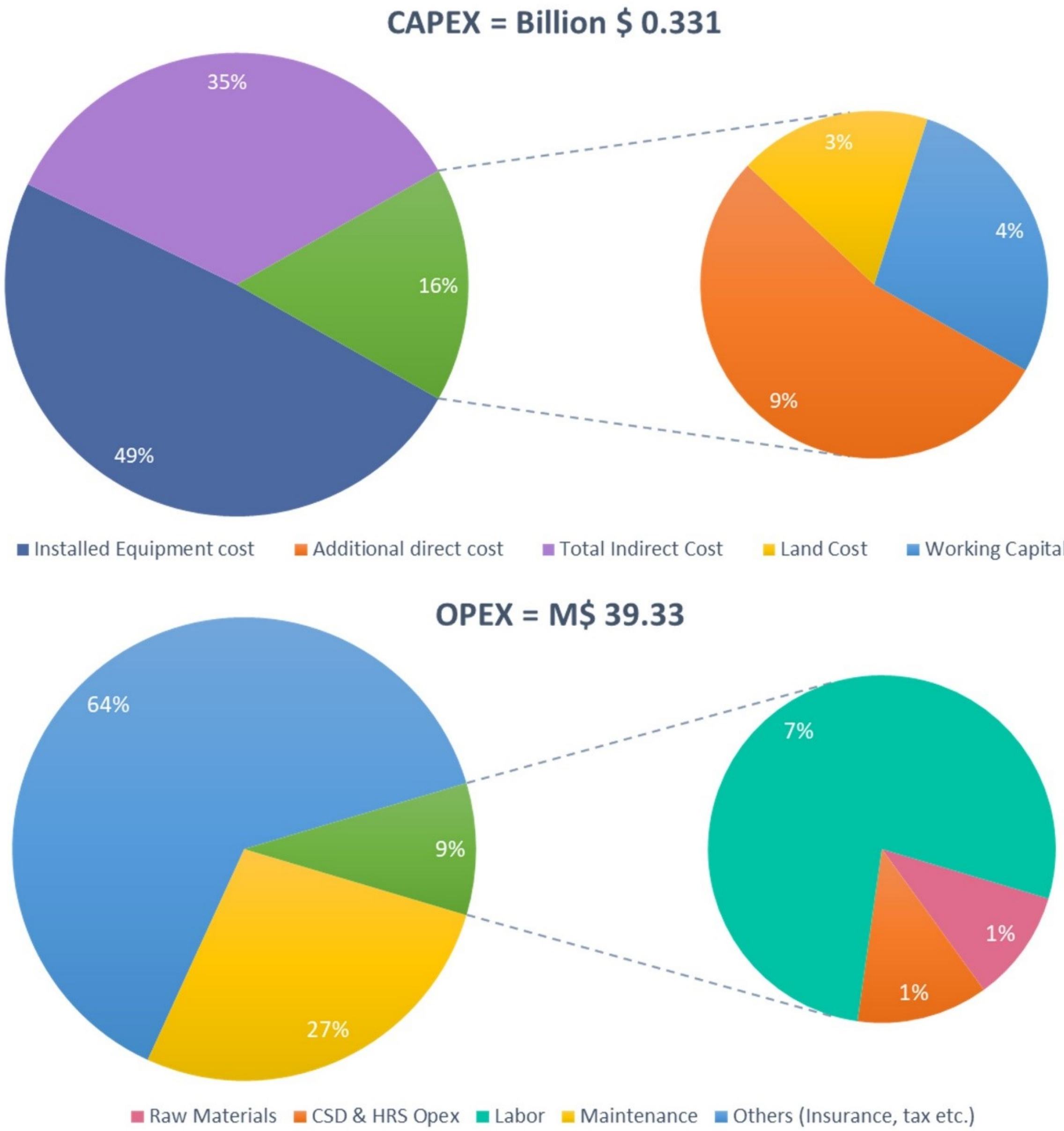

Fig.S 2. CAPEX and OPEX breakdown for Case 2.

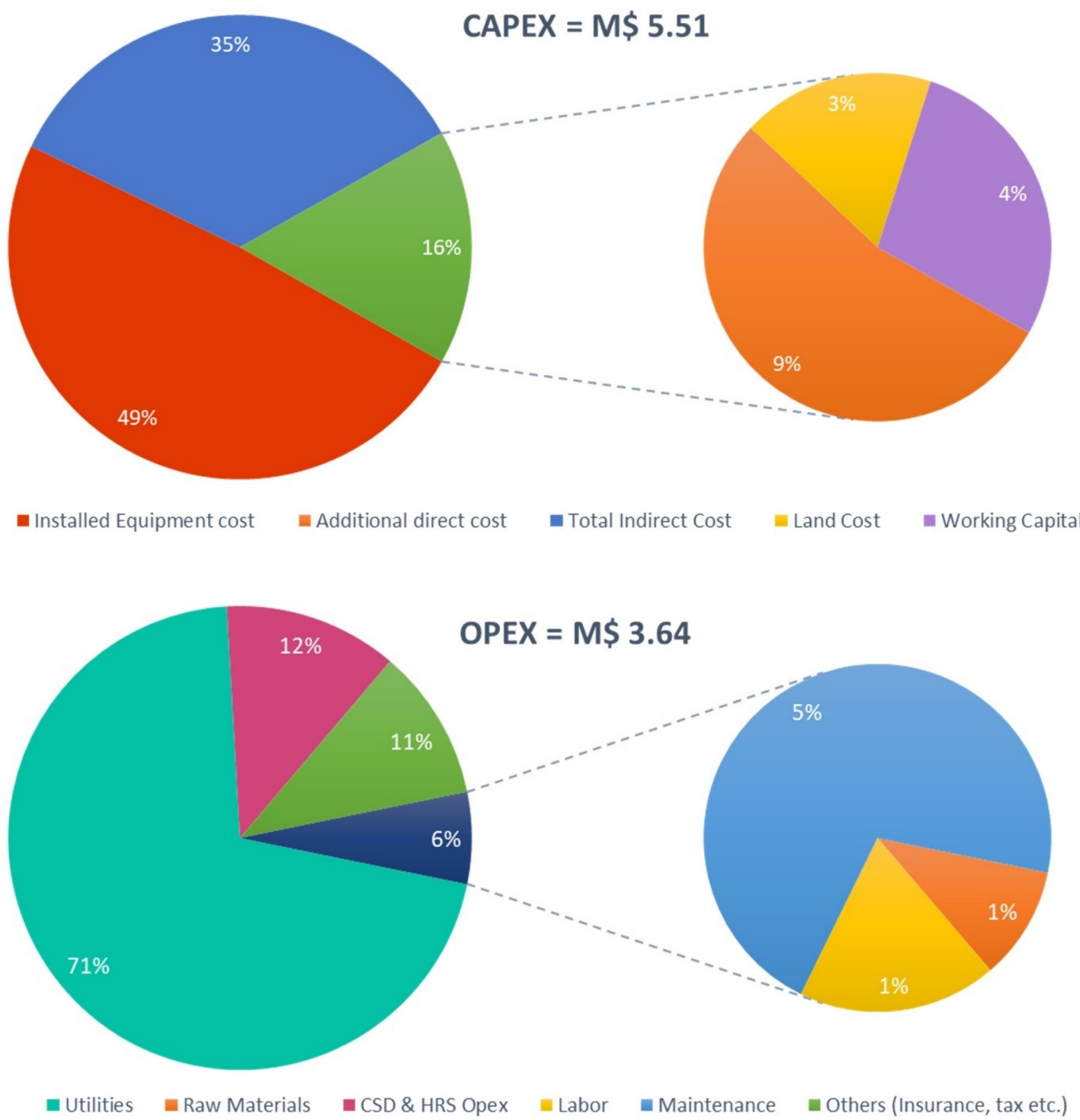

Fig.S 3. CAPEX and OPEX breakdown for Case 3.

Hydrogen delivery by tube trailer.

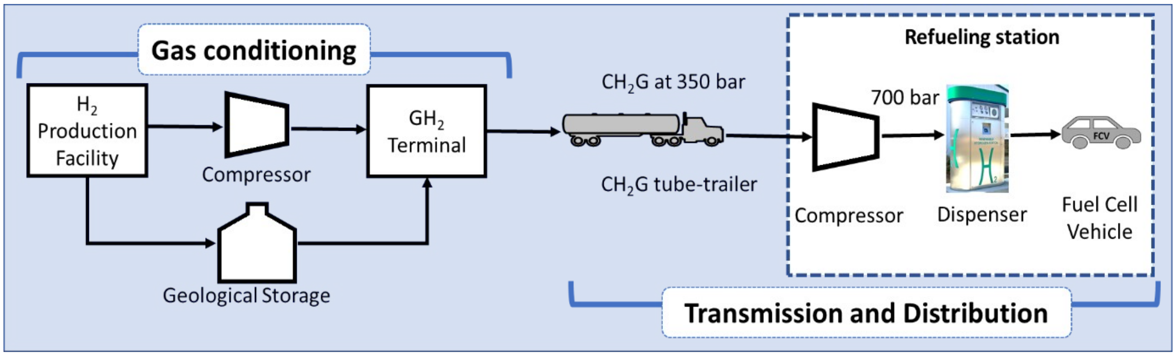

Fig.S 4. Hydrogen delivery as compressed gas by Tube trailer.

Life cycle assessment results of the studied cases.

As shown in **Fig. S 5**, the green ammonia production process has the highest impact in each environment indicator, which is due to the high amount of electricity used in the water electrolysis process. The breakdown of green ammonia production is also shown in **Fig.S 6**, which clearly demonstrate that more than 85% of the contribution to each indicator is from the hydrogen production process, as huge amount of electricity is required to produce hydrogen through water electrolysis. As we have also considered the infrastructure so most (more than 90%) of the emissions in hydrogen production are related to the production of electricity from solar PV power plant.

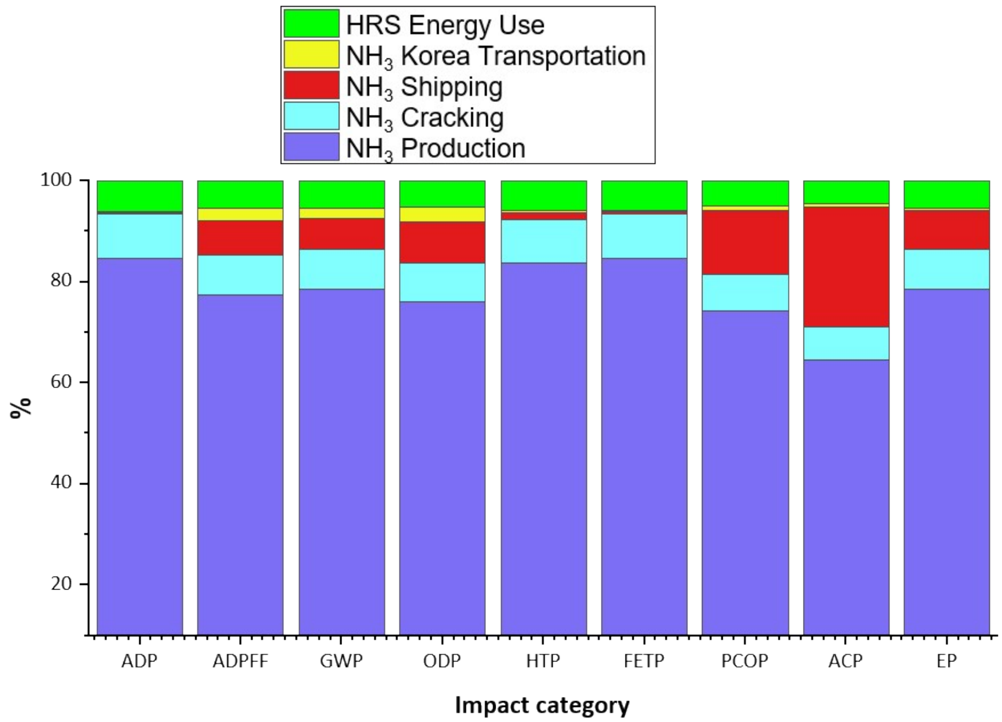

Fig.S 5. Breakdown of LCA results for Case 1.

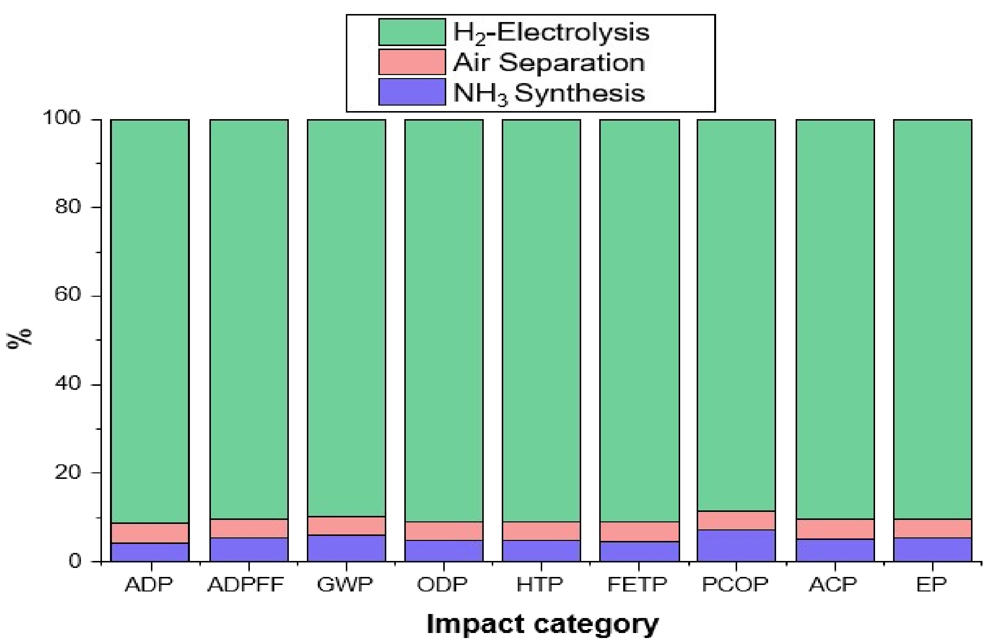

Fig.S 6. Breakdown of LCA results for green NH3 production.

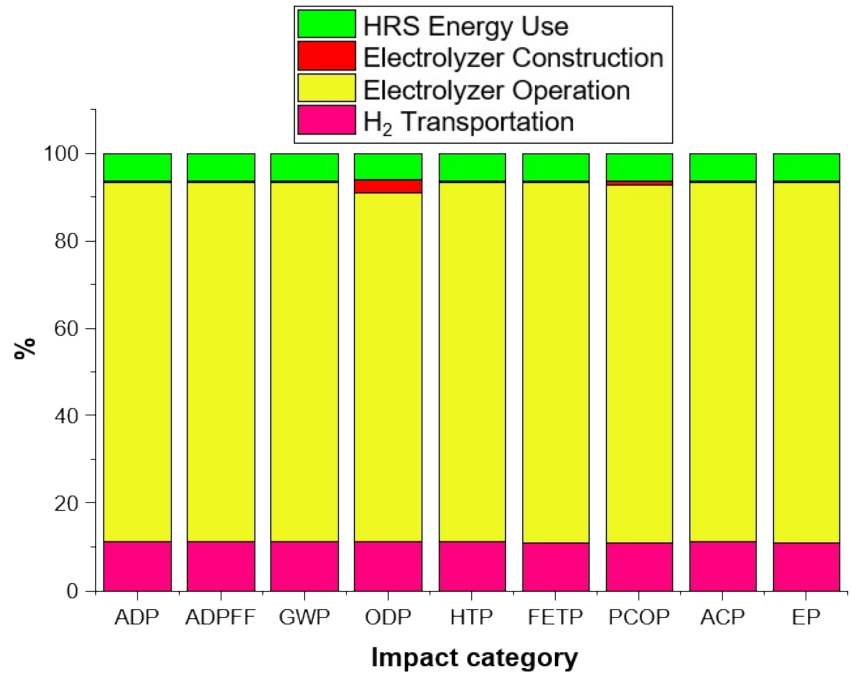

Fig.S 7. Breakdown of LCA results for Case 2.

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Fig.S 7 illustrates the breakdown of results for Case 2. Hydrogen transportation also has a significant contribution in each indicator following the electrolyzer operation stage owing to the burning of nonrenewable based fuel used during the transportation. **Fig.S 8** presents the breakdown of results for Case 3, showing that the electrolyzer construction contributes little to the emissions, whereas the energy used in the compression and dispensing of hydrogen has a more significant impact; however, hydrogen production is still the highest contributor. The production of electricity is the major contributor (99%) in the operational phase of the electrolyzer owing to the manufacturing of raw materials required for the solar PV power plant.

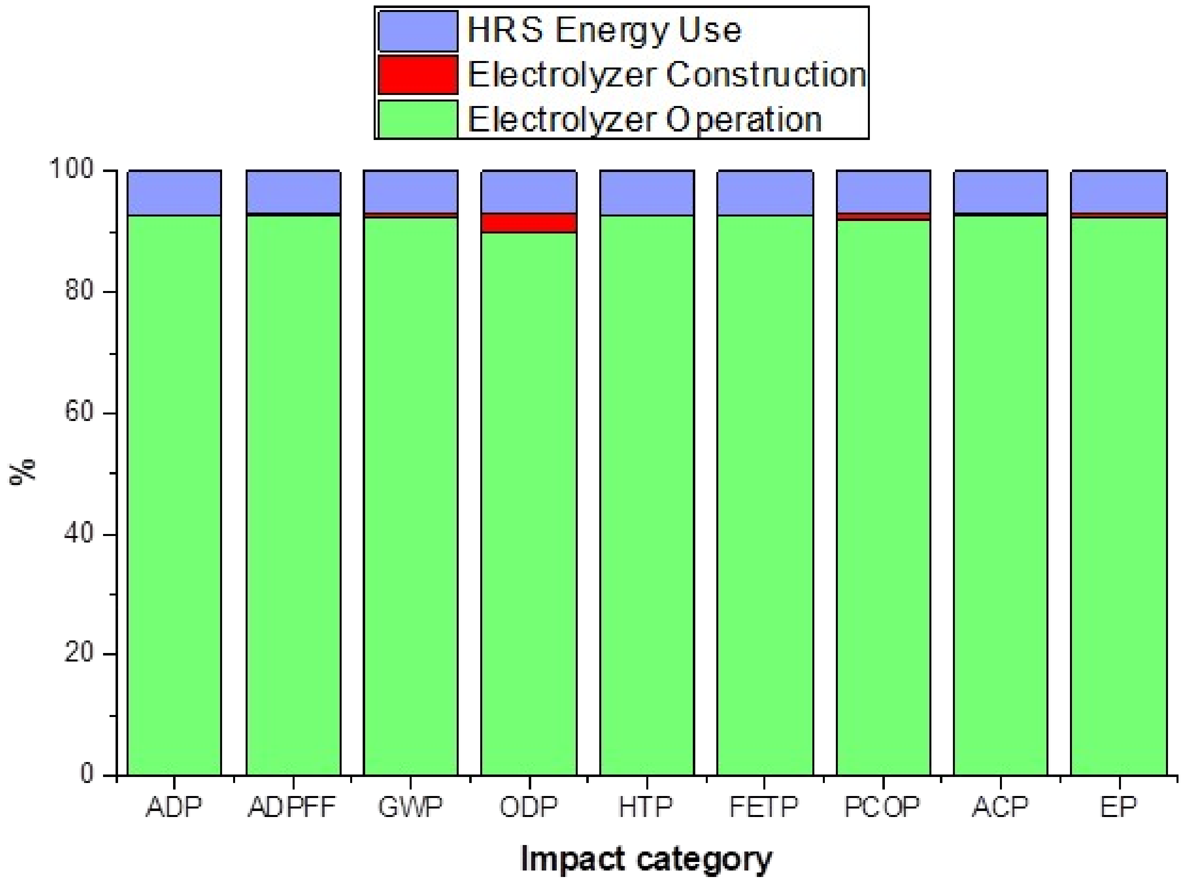

Fig.S 8. Breakdown of LCA results for Case 3.

References

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