Supporting Information

Demonstration of green hydrogen production using solar energy at 28% efficiency and evaluation of its economic viability

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Additional details of the TEA for making hydrogen (50 tons/ day) from water using CPV-E for 9.1 hours per day and direct electrolysis (from the grid) for 14.9 hours per day.

Capital and Working Parameters

plant lifetime (years)	20
H_2 Production (ton/day)	50
Sunshine (hours/day)	9.1
Night hours (hours/day)	14.9
H_2 Production Rate during day (ton/h)	2.08
H_2 produced by PV (ton/day)	18.96
H_2 produced by electricity (ton/day)	31.04
Annual Working Days (days/yr)	333
H_2 Production Rate from PV (ton/year)	6313.7
Total H_2 Production Rate (ton/year)	16150

PV Energy & land

PV lifetime (years)	20
Land factor	4
Power needed for Solar Farm (kW)	97,202.38
Energy produced by solar farm (kWh)	884,541.67
Solar Irradiation in Tabuk KSA (kWh/m^2)	7.37
PV module efficiency	41.00%
Power produced by PV module (kWh/m^2)	3.022
Area needed by PV modules (m^2)	2.93E+05
Total area required (m^2) including land factor	1.17E+06
module and tracker lifetime (years)	25.00
Module and tracker cost ($/W)	$ 0.720
Labor, Design, and installation ($/W)	$0.43
PV inverter ($/W)	$0.08
Total Module and tracker cost ($)	$69,985,714.29
Total cost of Labor, design, permitting and installation	$41,991,428.57
PV inverter cost ($)	$7,776,190.48
PV Farm turnkey Capital	$119,753,333.33
PV O&M cost (USD/kWh)	0.008
PV annual Opex	$7,076.33

Electrolyzer (Alkaline)

Reference Operating current density (A/cm^2)	0.40
Reference Operating voltage (V)	1.70
Actual operating current density	0.40
Pressure of H_2 (bar) before compression	10
electrical usage per kg of H_2 ($KWh_{elec}/kg(H_2)$) -LHV	32.66
Electrolysis efficiency (electrical efficiency) (1.23/1.7)	0.70
Fixed O&M (%) - of total uninstalled CAPEX	3.00%
Electrolyser replacement cost (% of uninstalled capes)	15.00%
Stack Cost of reference electrolyzer (USD/kW)	$272.00
Balance of plant capital cost includes power electronics (USD/kW)	$272.00
Electrolyzer installation factor	12.0%
Reference Stack cost ($/m^2)	1849.60
H_2 production (mol/day)	2.50E+07
electrons to make 1 H_2 molecule	2.00
electrons to make 1 mole of H_2	1.20E+24
total electrons needed per day (electrons/day)	3.01E+31
total charge (C /day)	4.82E+12
Amps (C / second)	5.58E+07
Area of electrolyzer (cm^2)	1.39E+08
Area of electrolyser (m^2)	13942.13
stack cost of electrolyser based on m^2 (USD)	$25,787,362.96
BOP cost (USD)	$25,787,362.96
installation cost of electrolyser (USD)	$6,188,967.11
Capex of electrolyzer stack, BOS & installation (USD)	$57,763,693.04
Yearly Opex of electrolyzer ($/year)	$1,547,241.78
Yearly electricity cost of ($/year)	$9,645,781.07
Electrode replacement time (years)	7.00
number of times electrodes will be replaced in plant lifetime	2.00
Electrolyzer replacement factor	1.5%
annual electrolyzer replacement cost (USD/yr)	$866,455.40
Electrolyzer annual Opex (USD/yr)	$2,413,697.17

Water pump, Compressor gas processing (to 20 bar)

Duty(kW)	51.94
Capex of pump	$29,306.58
Opex (USD/yr) of pump	$8,302.09
Duty (kW)	984.68
Opex (USD/hr)	$19.69
Capex (USD)	$4,143,572.97
Opex (USD/yr)	$157,391.09

Production using electricity

H_2 Production Rate (ton/h)	2.08
working hours/day	14.9
Power needed from grid (kW)	97202.38
Energy provided by grid (kWh)	1,448,315.48
Total system electrical usage at night for a year (kWh)	4.82E+08

Factors

KSA Location Markup Factor (1.0 for USA)	1.00
Land cost (USD/km^2)	$123,497.00
H_2 loss due to separation	3.0%

Operation Parameters

DI Water amount (ton/tonH_2)	10
DI Water price (USD/ton)	1.3
Annual water consumption (ton/yr)	166,500.00
Annual water cost (USD/yr)	$216,450.00
Required electricity for utilities (kWh/tonH_2)	161.00
Annual electricity requirement for utilities (kWh/yr)	2,680,650.00
Electricity price (USD/kWh)	0.02
Annual electricity cost (USD/yr)	$53,613.00
Number Plant Staff	10
Staff salary cost (USD/h)	20.00
Annual cost of plant staff (USD/yr)	$1,598,400.00

Revenue

Levelized H_2 Price (USD/ton)	$2,555
Annual H_2 revenue (USD/yr)	$41,257,830.32
Oxygen Credit (USD/ton O_2)	$40.00
Oxygen Credit (USD/ton H_2)	$320.00
Annual Oxygen Credit (USD)	$5,168,160.00
CO_2 Credit (USD/ton CO_2) based on stoichiometric ratio of the SMR reaction ($CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$) – excluding process energy.	$50.00
CO_2 Credit (USD/ton H_2)	$275.00
Annual CO_2 Credit (USD)	$4,441,387.50

Total Capex

PV Farm turnkey Capital	$119,753,333.33
Capex of electrolyzer stack, BOS & installation (USD)	$57,763,693.04
Compressor & gas processing (USD)	$4,143,572.97
Water pump	$29,306.58
Fixed Capital Cost (USD)	$181,689,905.92
Contingency	20.0%
Total Fixed Capital Cost in KSA + plus contingency (USD)	$218,027,887.10
Land Cost (USD)	$146,326.82
Working capital - (Installation Cost of whole plant) (USD)	$48,180,395.68

Annual Opex

Annual PV Maintenance (USD/yr)	$7,076.33
O&M of electrolyzer (USD/yr)	$2,413,697.17
Electricity cost to run electrolyzer + utilities ($/year)	$9,699,394.07
Compressor	$157,391.09
Water pump	$8,302.09
Annual water cost (USD/yr)	$216,450.00
Annual staff cost (USD/yr)	$ 1,598,400.00
Total Annual Variable Cost (USD/yr) (OPEX)	$14,100,710.76

Revenue

Annual H_2 Revenue	$41,257,830.32
annual oxygen + CO_2 credit	$9,609,547.50
Total Annual Revenue (USD/yr)	$ 50,867,377.82

Internal Rate of Return: IRR	12.0%

Effect of operation time and electricity cost on the Levelized Cost of Hydrogen from water.

50 tons H_2/day	CPV (9.1 hour operation)	**CPV + grid (24 hour operation) Electricity at 0.05 $/kWh**	**CPV + grid (24 hour operation) Electricity at 0.02 $/kWh**
Energy provided and power needed			
Power needed for the solar farm (kW)	256,357.93	97,202.38	97,202.38
Energy provided by the solar farm (kWh)	2,332,857.14	884,541.67	884,541.67
Energy provided by grid (kWh)	0	1,448,315.48	1,448,315.48
Capex			
Total solar farm cost ($)	$315,832,967.03	$119,753,333.33	$119,753,333.33
Total electrolysers capital ($)	$156,193,758.24	$57,763,693.04	$57,763,693.04
Opex			
Annual PV Maintenance ($/yr)	$18,662.86	$7,076.33	$7,076.33
Annual electricity cost ($/yr)	$134,032.50	$24,248,485.18	$9,699,394.07
Levelized H_2 Price ($/ton)	$5,900	$3,471	$2,555

At 0.05 $/kWh the LCH is found to be $3.47 the kg (a drop of $2.5 per kg when compared to a 9.1 hours/day operation). The effect of electricity, while important, seems to affect less the cost in the investigated range, a drop of $0.9 per kg_{H2} (ca. 25%) when the electricity dropped 2.5 times (from $0.05 to $0.02 the kWh; a 250% drop).

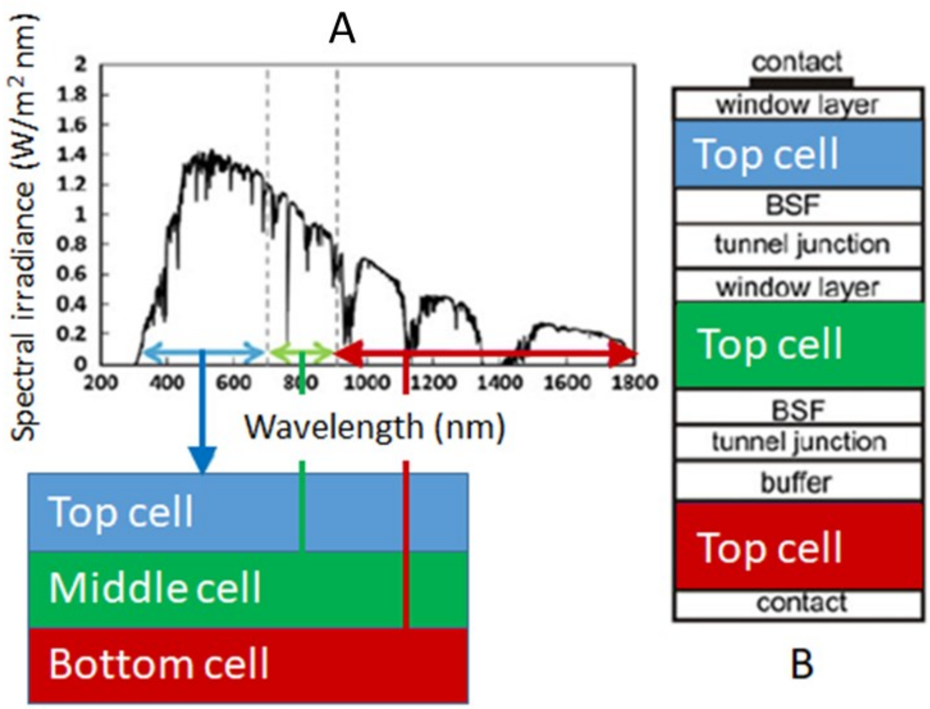

Figure S1. Part of the solar spectrum absorbed in a triple junction solar cell (A) and a schematic representation of a typical triple-junction solar cell (B) (adapted from ref. 1)

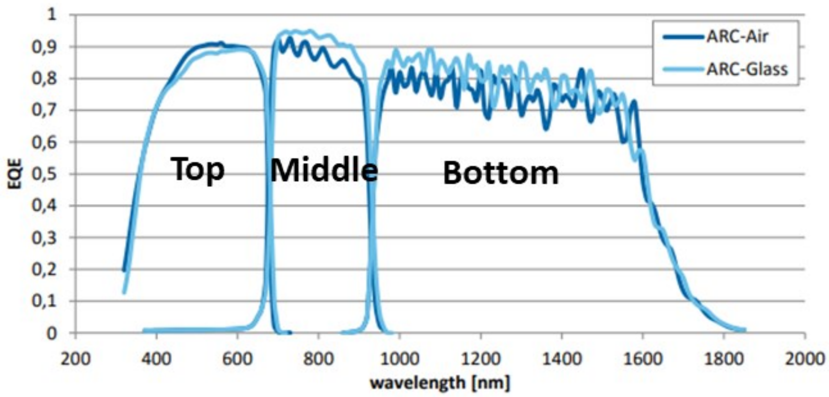

Figure S2. External quantum efficiency (EQE) of a GaInP/GaInAs/Ge AzurSpace solar cell (adapted from ref. 2).

References

1) Fernández, Eduardo F., Antonio J. García-Loureiro, and Greg P. Smestad. "Multijunction concentrator solar cells: analysis and fundamentals." High Concentrator Photovoltaics. Springer, Cham, 2015. 9-37.

2) http://www.azurspace.com/images/products/0004357-00-01_3C44_AzurDesign_3x3.pdf