Comparative Techno-economic Analysis of Different

Direct Solar Hydrogen Generation Systems

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SUPPLEMENTARY INFORMATION

Baseline costs

Table S1: baseline costs for different DSHG configurations

Component	Coupled PEC	Coupled PV-EC	Decoupled PV-EC	Ref
DSHG module				
PV module	238.5 $/kW	238.5 $/kW	238.5 $/kW	[1]
Membrane	50 $/m²	50 $/m²	50 $/m²	[2]
Catalyst	5.5 $/m²	5.5 $/m²	5.5 $/m²	[3]
Chassis and module assembling cost	140 $/kW	140 $/kW	140 $/kW	[4]
DC-DC convertor			100 $/unit	
Hard BoS				
Racking/mounting structure	64 $/kW	64 $/kW	64 $/kW	[1]
Piping	P5 – 4 $/m P4 – 4 $/m P3 – 6.18 $/m P2 – 6.18 $/m P1 – 8.51 $/m	P5 – 4 $/m P4 – 4 $/m P3 – 6.18 $/m P2 – 6.18 $/m P1 – 8.51 $/m	P5 – 4 $/m P4 – 4 $/m P3 – 6.18 $/m P2 – 6.18 $/m P1 – 8.51 $/m	[5, 6]
Gas compressor and condenser with intercoolers	220 $/kW	220 $/kW	220 $/kW	[7]
Water circulation	169 $/kW	169 $/kW	169 $/kW	[7]
Controllers and sensors water level controller, pressure sensor, hydrogen sensor, gas flow meter	525 $/unit (collective for all 4 controllers and sensors)	525 $/unit (collective for all 4 controllers and sensors)	525 $/unit (collective for all 4 controllers and sensors)	[6]
Wiring- signal, power and conduit	0.8 $/ft	0.8 $/ft	0.8 $/ft	[6]
Installation				
Mechanical installation and inspection	59 $/kW	59 $/kW	59 $/kW	[1]
Piping installation	29.6 $/kW	29.6 $/kW	29.6 $/kW	
Electrical installation	11.84 $/kW	11.84 $/kW	11.84 $/kW	
Soft BoS				

Margin	60.7 $/kW	60.7 $/kW	60.7 $/kW	[1]
Financing costs	32.6 $/kW	32.6 $/kW	32.6 $/kW	[1]
System design	9.1 $/kW	9.1 $/kW	9.1 $/kW	[1]
Permitting	14.08 $/kW	14.08 $/kW	14.08 $/kW	[1]
Incentive applications	8.94 $/kW	8.94 $/kW	8.94 $/kW	[1]
Customer acquisition	9.13 $/kW	9.13 $/kW	9.13 $/kW	[1]
Replacement costs				
Replacement catalyst cost	Catalyst cost for future year with 2.5% cost reduction per year and 1.9% inflation rate			
Replacement membrane cost	Membrane cost for future year with 2.5% cost reduction per year and 1.9% inflation rate			
Replacement of DSHG module cost	cost for future year with 2.5% cost reduction per year and 1.9% inflation rate			
Replacement components installation costs	50% of mechanical installation cost	50% of mechanical installation cost	50% of mechanical installation cost	[1]
DSHG O&M costs*	10 $/kW/yr	10 $/kW/yr	10 $/kW/yr	[1]
piping O&M costs*	10 $/kW/yr	10 $/kW/yr	10 $/kW/yr	
Water costs*	3.9 $/kGal/yr			[8]

*An inflation rate of 1.9% per year is considered while calculating these costs

**Cost reduction of 2.5% per year for future assuming production will scaleup exponentially

Table S2: baseline costs for PV-E configuration

Component	cost	ref
PV system		
Module and invertor hardware		
PV module	238.5 $/kW	[1]
Invertor	33.43 $/kW	[1]
BoS hardware		
Racking and mounting	43.30 $/kW	[1]
Cabling/wiring	30.57 $/kW	[1]
Safety and security	17.47 $/kW	[1]
Monitoring and control	3.20 $/kW	[1]
Installation		
Mechanical installation	50.28 $/kW	[1]
Electrical installation	36.1 $/kW	[1]
Inspection	8.93 $/kW	[1]
Soft BoS		
Margin	60.7 $/kW	[1]
Financing costs	32.6 $/kW	[1]
System design	9.1 $/kW	[1]
Permitting	14.08 $/kW	[1]
Incentive applications	8.94 $/kW	[1]
Customer acquisition	9.13 $/kW	[1]

Electrolyzer system		
PEM stack		
Porous transport layer (PTL)	61.2 $/kW	[9] [7]
Small parts (sealing, frames)	10.8 $/kW	[9] [7]
Bipolar plates	190.8 $/kW	[9] [7]
Stack assembly and end plates	10.8 $/kW	[9] [7]
Catalyst coated membranes Manufacturing PFSA membrane Iridium Platinum	 36 $/kW 17.6 $/kW 21.6 $/kW 11.2 $/kW	[9] [7]
Hard BoS		
Power supply	220 $/kW	[9] [7]
Deionized water circulation	96.8 $/kW	[9] [7]
Hydrogen processing	88 $/kW	[9] [7]
Cooling	35.2 $/kW	[9] [7]
O&M		
For PV*	10 $/kW/yr	[1]
For electrolyzer*	3% of electrolyzer capital cost	[10]
Water*	3.9 $/KGal/yr	[8]
Replacement cost		
Catalyst	Catalyst cost for future year with 2.5% cost reduction per year** and 1.9% inflation rate	
Replacement material installation cost		

*An inflation rate of 1.9% per year is considered while calculating these costs

**Cost reduction of 2.5% per year for future assuming production will scaleup exponentially

Table S3: cost range for DSHG configurations. All the costs are color coded in red, yellow and green based on the level of uncertainty in the costs, where green are least uncertain, and red are the most.

Variable	Baseline	Min	Max	Range
Capacity factor	20	22	20	
Discount rate	8	5	8	
DSHG Module				
PV module	238.5 $/kW	238.5 $/kW	263.65 $/kW	[1]
Catalyst cost	5.5 $/m2	0 $/m2	8 $/m2	[3]
DC-DC convertor	100 $/unit	0 $/m2		
Membrane cost	50 $/m2	30 $/m2	180 $/m2	[2]
Membrane and catalyst lifetime	5 years	5	5	
Hard BoS				

Racking and mounting	64 $/kW	64 $/kW	111.25 $/kW	Min- current value, Max- mid PV range values [1]
Electrolyte and Gas handling (compressors and pumps)	220 $/kW	165 $/Kw	495 $/kW	IEA [11] and NREL [7]
Piping material	30 $/kW	30	45	Min plastic, max steel
Controllers and sensors	20 $/kW	0	**1200 $/kW**	500% increase in cost
Installation and other soft BoS				
Mechanical and electrical installation	71 $/kW	71 $/kW	120 $/kW	Min- current value, Max- mid PV range values [1]
Other soft BoS	135 $/kW	135 $/kW	183 $/kW	Min- current value, Max- mid PV range values [1]
Piping installation	30$/kW	30	60	Piping installation cost ~ total material cost
O&M				
DSHG	10 $/kW	10	18	[1]
piping	10 $/kW	5	18	[1]
Replacement				
Replacement materials installation costs	30 $/kW	15	45	± 50%

Table S4: cost range for PV-E configurations

Component	baseline	min	max	
PV system ($/kW)	596	596	952	Min- current value, Max- mid PV range values [1]
Electrolyzer ($/kW)	800	560	1800	IEA [11] and NREL [7]
PV O&M cost ($/kW/yr)	10	10	18	[1]
Piping O&M cost ($/kW/yr)	10	5	18	[1]
Replacement materials installation costs (% of original cost)	30	15	45	± 50%

Module specifications

The performance and size parameters of commercially available LG R series Si PV module – LG435QAC, are used in the current work. The specifications of the module are given in detail in the below tables.

Table S5: Dimensions and layout of Si PV module

No of cells	66	
module width	40.94	inch

	104	cm
module length	75.2	inch
	191	cm
Area	19864	cm^2
Cell area	300.97	cm^2
Coverage	86.8	%

Table S6: Dimensions and layout of DSTH module

No of cells	66	
Length	191	cm
Width	104	cm
Area	19864	cm^2
Depth	0.1	cm
Volume	1986.4	cm^3
Volume	1.9864	L

Table S7: Operating parameters of the PV and DSTH module

Parameter		value	unit
Output power	P$_{max}$	435	Watt
Voltage at maximum power point	V$_{mpp}$	41.1	Volts
Current at maximum power point	I$_{mpp}$	10.6	Ampere
Open circuit voltage	V$_{oc}$	48	Volts
Short circuit current	I$_{sc}$	11.2	Ampere
Fill factor	FF	80.9	%
PV module efficiency	η	21.9	%
STH efficiency for coupled configuration (calculated)	STH	15.26	%
STH efficiency for decoupled configuration (calculated)	STH	20.60	%

Hydrogen production rates

The hydrogen production rates for the given module design and STH efficiency are calculated using the operating current density. The hydrogen production rate is then extended to the module and plant level.

$$\text{Rate of hydrogen production per area } (gm/s/cm^2) = \frac{J_{op}\ (A/cm^2)\times 1.23(V)}{calorific\ value\ of\ hydrogen(J/gm)}$$

Rate of hydrogen production per cell = size of cell (cm^2) x rate of hydrogen production per area

Rate of hydrogen production per module = cells per module x rate of hydrogen production per cell

Component costs from utility scale PV plants

Different costs: are taken from utility scale PV plants. We took the detailed cost values for different countries from IRENA power generation report 2021 [1] and used standard deviation to define the low, mid, and high-cost ranges. Figure S1(a) shows the total cost of different components of interest for different countries in $/kW directly taken from the IRENA power generation report.
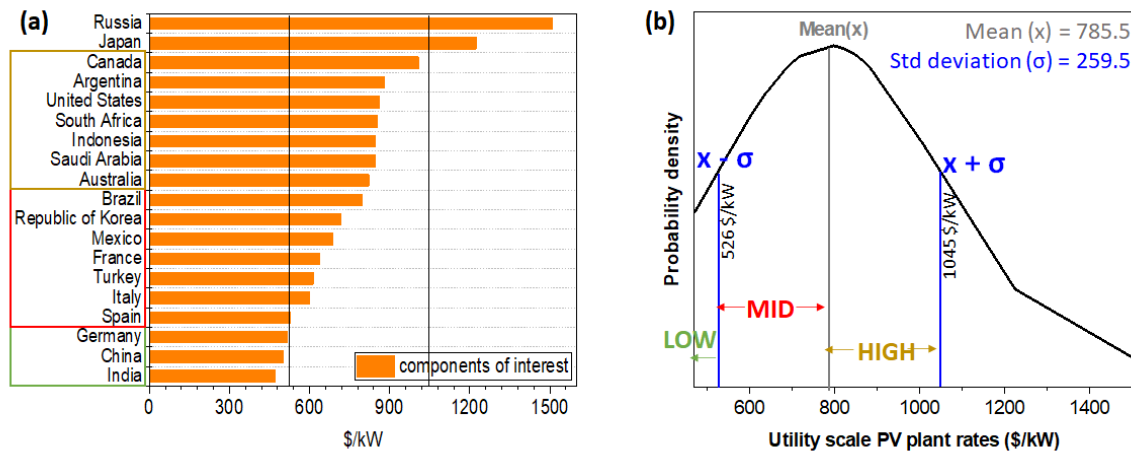

Figure S1: (a) Utility scale PV costs for different countries from IRENA report (b) standard deviation curve and low, mid, and high ranges

Figure S1(b) shows the standard deviation curve for utility scale PV costs of interest for different countries. The low and mid-range for the utility-scale PV plant is set by taking one and two standard deviations of values lower than mean respectively, while the high range is defined by taking one standard deviation of values higher than mean, assuming that no renewable hydrogen plants would be built in the most expensive places.
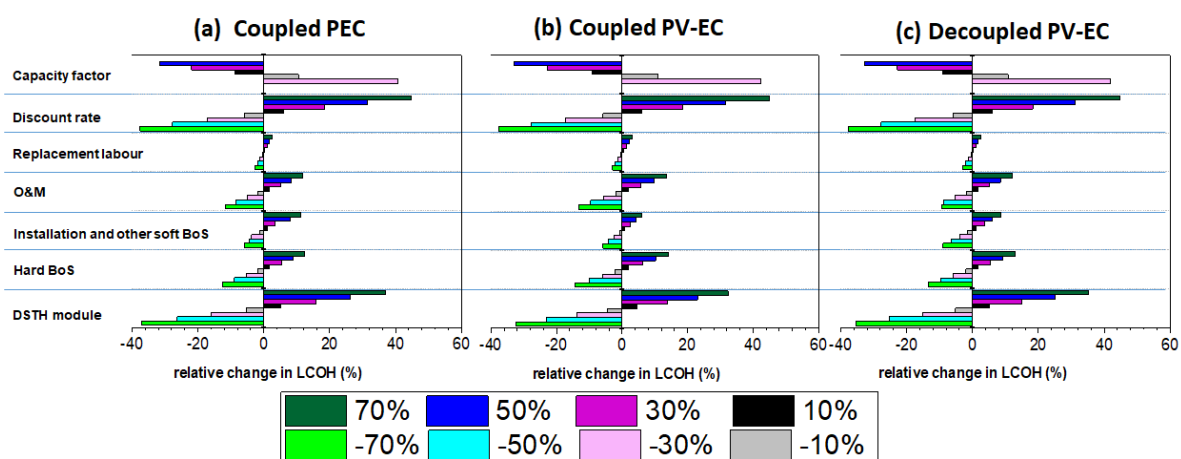
Sensitivity analysis

Figure S2: Sensitivity analysis for the DSHG systems based on the costs of PV panel, membrane, PEC panel, Hard BoS, soft BoS, Discount rate and capacity factor. Each analysis represents the relative change in LCOH values (x-axis) from the base value (as shown in figure 3(a), for low PV cost) on varying a single parameter.

Regression analysis

Table S8 shows list of the list of components, associated regression coefficients β_x , standard error (SE$_x$) and t-values (t$_x$) for all the three DSHG systems. Regression estimates are used to estimate the impacts of individual (or combinations) of variables, while holding all other factors constant. For a linear regression like this, the coefficients are the marginal change in the LCOH for changes in that factor. All the costs are color coded in red, yellow and green based on the level of uncertainity in the costs, where green are least uncertain, and red are the most. The significance of individual parameters in each configuration is quantified using   t-statistics 't$_x$', calculated using equation 3. A higher t-statistics value signifies higher dependence of the LCOH on the cost estimate associated with that parameter.

Table S8: Regression coefficient and t-values for different components for three different DSHG configurations.

| term	Coupled PEC					Coupled PV-EC					Decoupled PV-EC				
	estimate	Std. Error	t value	Pr(>|t|)		estimate	Std. Error	t value	Pr(>|t|)		estimate	Std. Error	t value	Pr(>|t|)	
Panel	0.01004	0.000347	28.98	< 2e-16	***	0.0037250	0.0002052	18.15	< 2e-16	***	0.002563	0.000272	9.417	2.5E-16	***
Membrane	0.00948	0.000111	85.66	< 2e-16	***	0.0095080	0.0000745	127.7	< 2e-16	***	0.006941	9.25E-05	75.04	< 2e-16	***
Catalyst	0.0095	0.000993	9.57	< 2e-16	***	0.0103900	0.0008822	11.77	< 2e-16	***	0.006607	0.000838	7.882	1.2E-12	***
lifetime	0.00691	0.000285	24.28	< 2e-16	***	0.0042360	0.0001922	22.04	< 2e-16	***	0.003142	0.000234	13.42	< 2e-16	***
chassis	0.00371	0.000402	9.231	8.6E-16	***	0.0037600	0.0002693	13.96	< 2e-16	***	0.002313	0.000354	6.525	1.4E-09	***
DC-DC convertor											0.000588	0.000547	1.077	0.28361	
racking	0.00413	0.000814	5.072	1.38E-06	***	0.0042240	0.0005460	7.736	3.07E-12	***	0.002479	0.000313	7.925	9.7E-13	***
piping material	0.00325	0.000453	7.176	5.6E-11	***	0.0032430	0.0003019	10.74	< 2e-16	***	0.002226	0.000278	7.994	6.7E-13	***
handling	0.00352	0.000256	13.73	< 2e-16	***	0.0035600	0.0001712	20.8	< 2e-16	***	0.002291	0.000227	10.08	< 2e-16	***
water	0.00279	0.001067	2.614	0.01004	*	0.0029190	0.0007186	4.062	8.5E-05	***	0.001982	0.000885	2.239	0.0269	*
sensors	0.00342	0.000894	3.826	0.00021	***	0.0035940	0.0006024	5.966	2.3E-08	***	0.002065	0.000752	2.744	0.00694	**
installation	0.00363	0.000568	6.399	2.8E-09	***	0.0037480	0.0003819	9.814	< 2e-16	***	0.00229	0.000483	4.737	5.7E-06	***
soft BoS	0.00341	0.000277	12.29	< 2e-16	***	0.0034350	0.0001863	18.43	< 2e-16	***	0.002312	0.000235	9.84	< 2e-16	***
piping installation	0.00338	0.0003	9.994	< 2e-16	***	0.0033810	0.0003383	9.994	< 2e-16	***	0.002266	0.000415	5.458	2.4E-07	***
piping OnM	0.00331	0.000156	21.15	< 2e-16	***	0.0033280	0.0001051	31.67	< 2e-16	***	0.004689	0.000133	35.35	< 2e-16	***
rest OnM	0.00331	0.000156	21.15	< 2e-16	***	0.0033280	0.0001051	31.67	< 2e-16	***	0.004247	0.000125	33.93	< 2e-16	***
replacement	0.01122	0.000502	22.37	< 2e-16	***	0.0112600	0.0003383	33.27	< 2e-16	***	0.004536	0.000428	10.61	< 2e-16	***
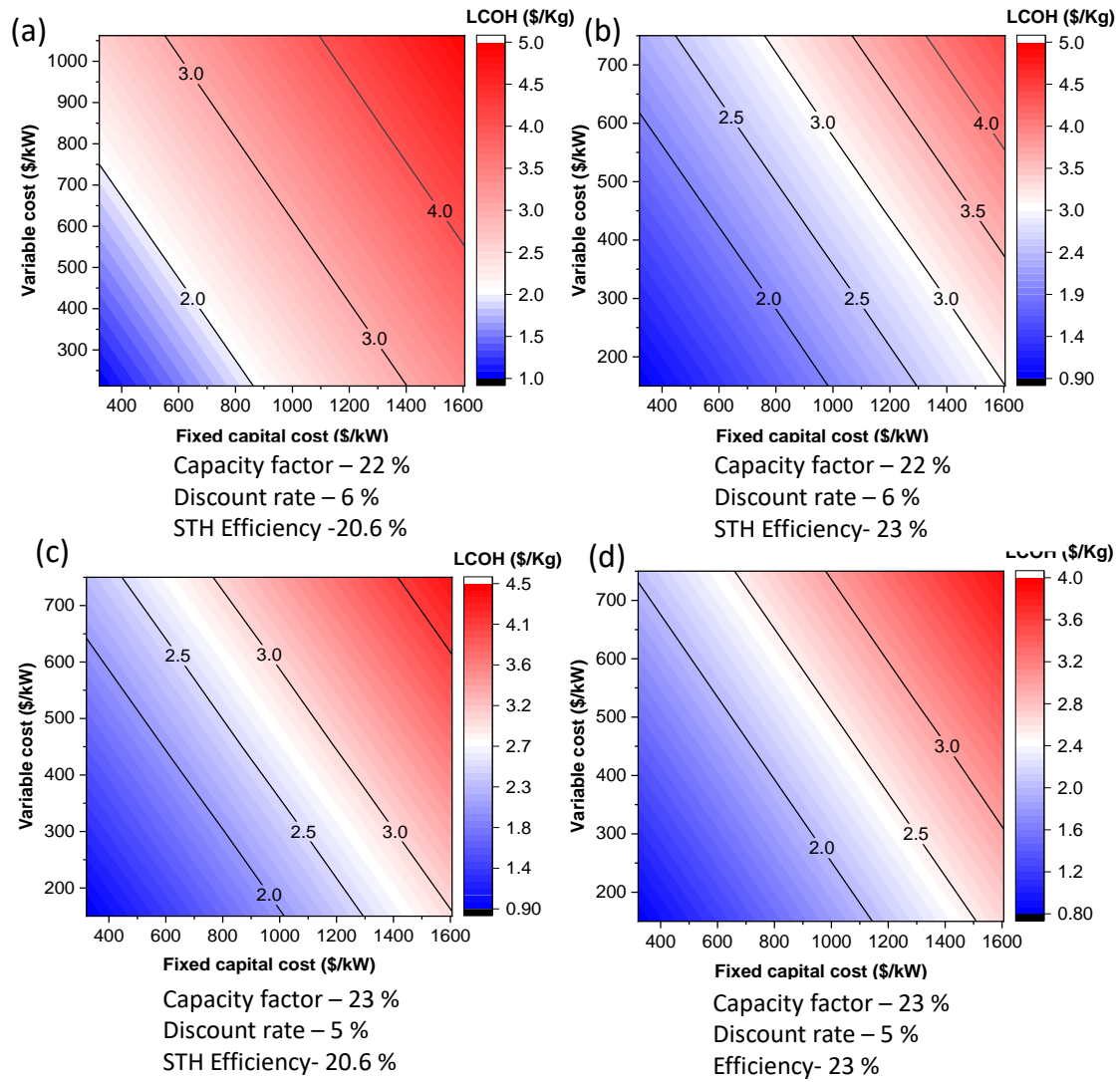
Figure S3: LCOH surface plot for different STH efficiency, capacity factor and discount rates

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