Evaluating the Costs of Integrated Solar Hydrogen Systems: Exploring the Effect of Scale, Intermittency, and Energy Storage

Jonathan Moncada [a,*], Bryan de Goeij [b], Jonathan van den Ham [c], Pascal Buskens [c,d], Nicole Meulendijks [c], Remko J. Detz [a]

[a] The Netherlands Organisation for applied scientific research (TNO), Energy Transition Studies, Amsterdam, the Netherlands
[b] The Netherlands Organisation for applied scientific research (TNO), Space Systems Engineering, Delft, The Netherlands
[c] The Netherlands Organisation for Applied Scientific Research (TNO), Materials Solutions, Eindhoven, The Netherlands
[d] Hasselt University, Institute for Materials Research, Design and Synthesis of Inorganic Materials (DESINe), Diepenbeek, Belgium

Supplementary Information

1. Solar irradiation information and capacity utilization rate

Table S1 presents the daily irradiation data for Huelva, Spain, used in the modelling of hydrogen production. Figure S1 displays the capacity utilization rate profile at different times of the day and throughout the year in Huelva, Spain, without intermediate storage.

Time of the day	January	February	March	April	May	June	July	August	September	October	November	December
00:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
01:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
02:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
03:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
04:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
05:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
06:00	0%	0%	0%	1%	4%	5%	4%	2%	0%	0%	0%	0%
07:00	0%	0%	5%	13%	17%	17%	16%	14%	12%	7%	0%	0%
08:00	11%	17%	25%	32%	37%	37%	36%	35%	34%	29%	21%	13%
09:00	34%	38%	45%	51%	56%	56%	56%	56%	53%	49%	41%	36%
10:00	53%	56%	62%	67%	72%	72%	75%	75%	72%	66%	58%	53%
11:00	63%	70%	74%	79%	84%	85%	88%	89%	85%	76%	68%	65%
12:00	70%	76%	80%	85%	89%	91%	95%	96%	91%	80%	72%	69%
13:00	68%	78%	81%	84%	88%	90%	95%	95%	91%	78%	69%	66%
14:00	62%	72%	75%	77%	79%	83%	88%	87%	81%	68%	58%	57%
15:00	50%	59%	62%	64%	66%	69%	73%	73%	67%	53%	44%	45%
16:00	34%	42%	44%	45%	47%	51%	55%	53%	46%	34%	25%	26%
17:00	8%	20%	23%	26%	27%	30%	33%	31%	23%	11%	1%	0%
18:00	0%	0%	4%	7%	9%	11%	12%	10%	3%	0%	0%	0%
19:00	0%	0%	0%	0%	1%	3%	3%	1%	0%	0%	0%	0%
20:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
21:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
22:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
23:00	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure S1. Capacity utilization rate profile at different times of the day and month in Huelva, Spain. Result analogous to all capacities and systems without intermediate storage

* Corresponding author.
Energy Transition Studies, TNO, Radarweg 60, 1043 NT, Amsterdam, The Netherlands. E-mail: jonathan.moncadabotero@tno.nl

Table S1. Solar irradiation data for Huelva, Spain. Adapted from the JRC Photovoltaic Geographical Information System (PVGIS) [1].

Time of the day	Solar irradiation information W/m^2											
	January	February	March	April	May	June	July	August	September	October	November	December
0:00	0	0	0	0	0	0	0	0	0	0	0	0
1:00	0	0	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	9	40	50	39	16	0	0	0	0
7:00	0	0	49	131	172	175	159	143	124	74	1	0
8:00	109	173	248	319	368	367	363	352	337	294	215	130
9:00	335	381	452	505	556	557	563	564	529	490	411	356
10:00	528	561	622	674	721	723	747	754	716	656	579	532
11:00	632	701	743	793	837	847	882	891	847	764	684	651
12:00	703	758	795	849	893	913	952	956	912	798	716	692
13:00	680	778	814	835	877	898	951	952	908	779	691	664
14:00	618	716	754	769	791	828	875	872	806	679	578	568
15:00	502	587	617	645	658	694	735	726	666	528	442	450
16:00	340	417	436	454	475	507	546	530	462	337	253	259
17:00	78	200	234	256	274	303	330	309	230	114	8	0
18:00	0	0	37	72	90	111	123	99	31	0	0	0
19:00	0	0	0	0	10	31	30	6	0	0	0	0
20:00	0	0	0	0	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0

2. Reference PV-E system

A reference PV-E system was modelled to compare the results with the integrated solar hydrogen panels system. In this reference system (System 2 from now on) PV panels generate electricity that is used in separate electrolyzers to produce hydrogen. Similar to the integrated solar hydrogen panels system (System 1), System 2 consists of four sections (refer to Figure S2): i) water conditioning and recycling, ii) electricity production and electrolysis, iii) hydrogen purification, and iv) hydrogen compression. The processes of water conditioning and recycling, hydrogen purification, and hydrogen compression in System 2 mirror those described for System 1. The key distinction between the two systems lies in the method of hydrogen production. In System 2, electricity is initially generated using silicon perovskite tandem photovoltaic (PV) panels, achieving an energy conversion efficiency of 25%. This generated electricity is then supplied to a Proton Exchange Membrane (PEM) electrolyzer, where it is transformed into hydrogen with an energy efficiency of 72%. Although the fundamental operation of this system differs from System 1, parameters were standardized across both systems to facilitate a more equitable and direct comparison. To address the variability of solar energy, System 2 incorporates the use of a battery for intermediate electricity storage, as described by [2]. Electricity stored in this battery serves as the input for electrolysis, ensuring that the downstream processing remains identical to that detailed in the body of the paper for System 1.

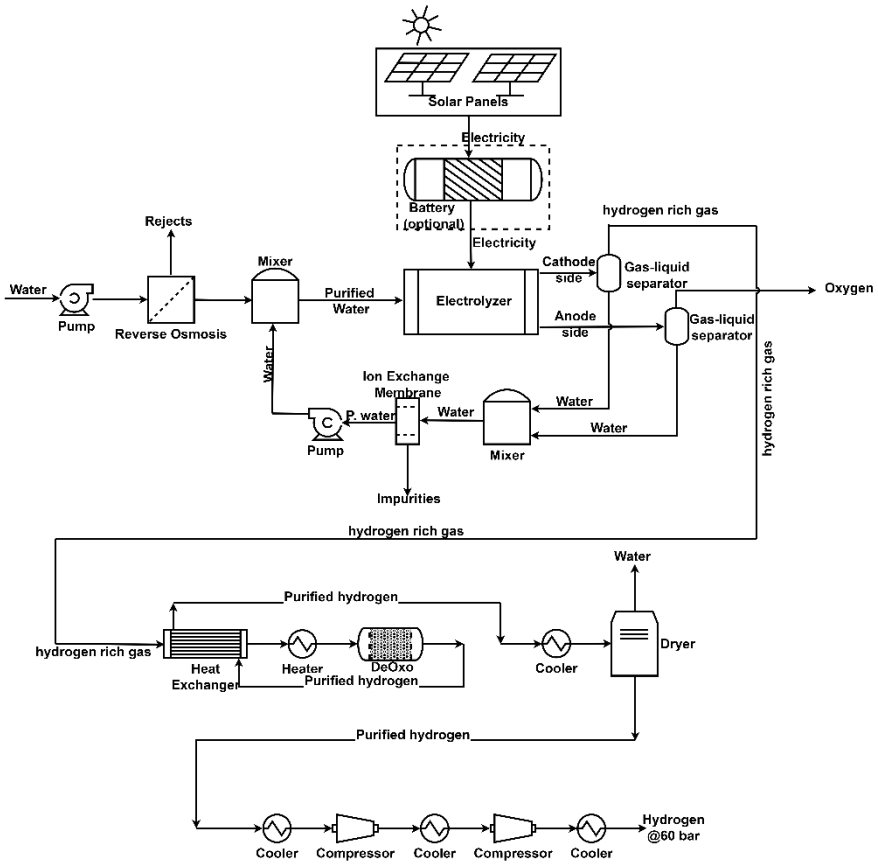


Figure S2. Flowsheet diagram of solar hydrogen production using detached PV and electrolyzer (System 2).

3. Operational results

3.1. Integrated solar hydrogen panels system

In Figure S3 (a) (1k panels), hydrogen storage follows a seasonal accumulation pattern. Surplus hydrogen is stored during the summer months when solar availability is high and is gradually depleted in colder months due to reduced production. The sharp discharge events observed are not necessarily related to seasonal energy demand but result from the need to maintain a continuous hydrogen supply for the downstream process. Even during periods of low solar production, hydrogen must be supplied to this process for as many hours as possible to optimize economic performance.

In contrast, Figure S3 (b) (100k panels) and S3 (c) (10M panels) show a different storage profile, where hydrogen storage becomes less dependent on seasonal variations. Instead of accumulating long-term reserves, storage mainly buffers short-term fluctuations in supply and demand on a daily basis. As system scale increases, hydrogen production becomes more stable, aligning more effectively with demand and reducing the need for extensive seasonal storage.

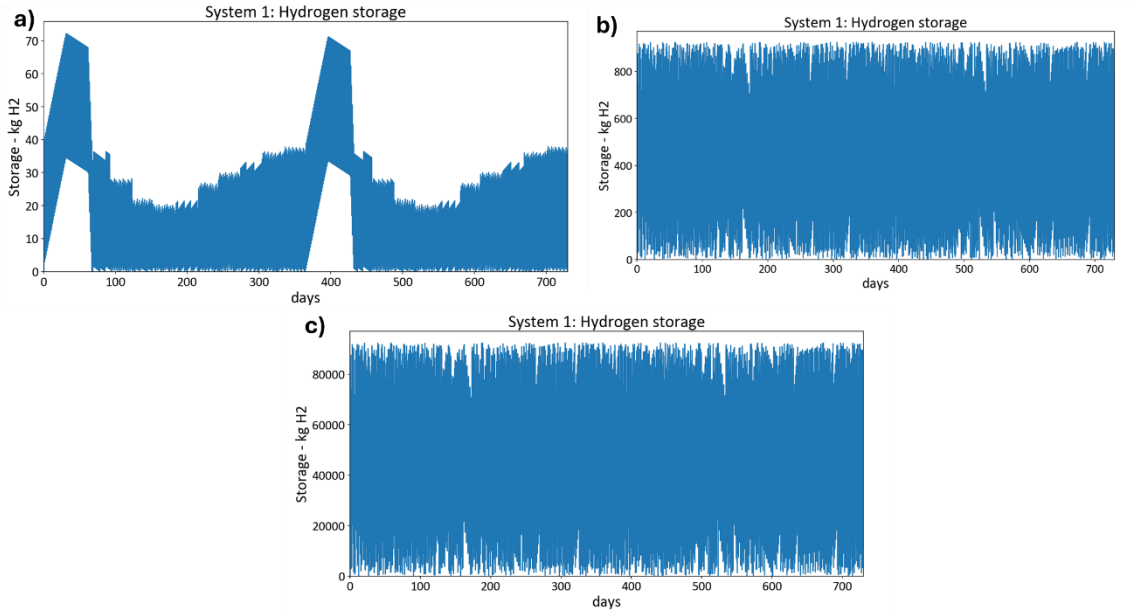


Figure S3. Hydrogen storage profiles in System 1 at the different operating capacities: a) 1k panels (operating hours: 6939 h/y), b) 100k panels (operating hours: 2267 h/y), c) 10M panels (operating hours: 2267 h/y).

3.2. PV-E system

For the detached PV and electrolysis system (System 2), the intermediate energy storage can be implemented in two ways. One option is to store hydrogen, which would be identical to the solar hydrogen system. The alternative is to store electricity between the PV panels and the electrolyzer. This approach allows for the downsizing of all equipment located after the battery, including the electrolyzer, the deoxygenation stage, the drying stage, and the compression stages. This differs significantly from the solar hydrogen system, where only the compression stage can be downsized.

The results show that for a system with 1,000 panels, the operating hours per year (downstream from the battery, See Figure S2) can be increased to 6,759 hours, which is approximately three times higher than the operating time of a system without intermediate electricity storage. For a system with

100,000 panels, the downstream operates for 6,452 hours per year, and for a system with 10 million panels, the downstream operates for 5,400 hours per year. The findings suggest that the impact of electricity storage is more significant for small-scale systems compared to large-scale systems. The profiles of intermediate electricity storage are provided in Figure S4. In Figure S4 (a) (1k panels), electricity storage exhibits a seasonal accumulation pattern, with energy being stored during the summer months when solar production is high and gradually depleting in colder months due to reduced solar availability. However, alongside this seasonal trend, storage levels also fluctuate on a daily basis, indicating frequent charge and discharge cycles that help balance short-term variations in energy production and demand.

In Figure S4 (b) (100k panels) and S4(c) (10M panels), a similar seasonal pattern is observed, but at a much larger scale, with increased overall electricity storage capacity. Despite the significant increase in storage size, distinct daily fluctuations remain prominent, suggesting that even in large-scale systems, energy storage continues to play a crucial role in managing short-term supply and demand variations.

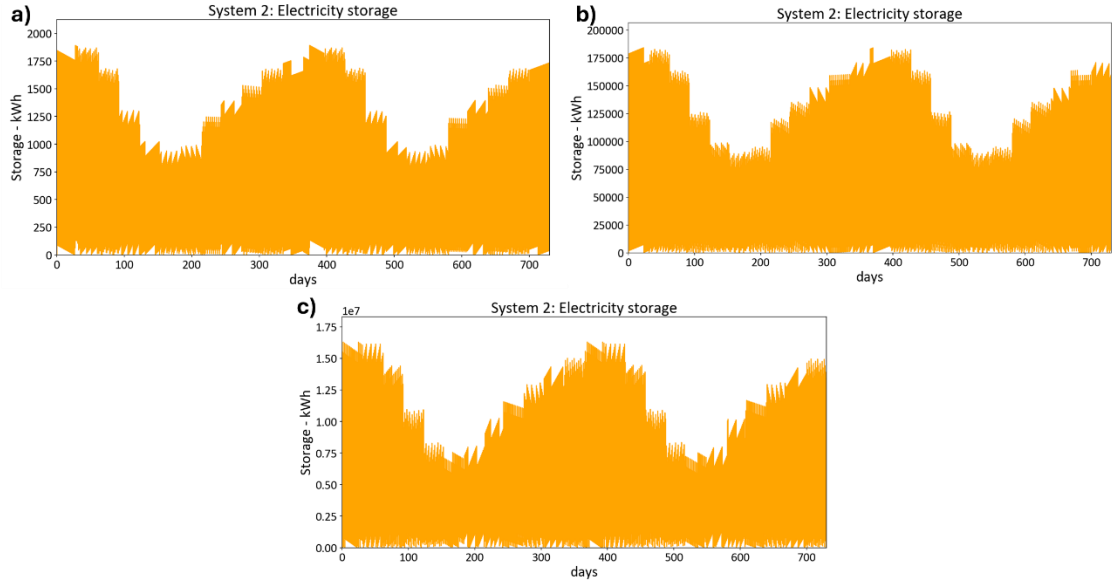


Figure S4. Electricity storage profiles in System 1 at the different operating capacities a) 1k panels (operating hours: 6759 h/y), b) 100k panels (operating hours: 6452 h/y), c) 10M panels (operating hours: 5400 h/y).

4. Investment cost

Capital investment is estimated for the main components of the integrated solar hydrogen system and the PV-E system. The integrated solar hydrogen system includes solar hydrogen panels, PV panels, balance of plant, hydrogen storage tank, and battery. The PV-E system includes PV panels, electrolyzer, balance of plant, and battery. Each component has a specific cost structure, which is described below. For all components, the investment cost includes direct costs, indirect and owner costs, working capital, and contingency.

4.1. Integrated solar hydrogen panels

4.1.1. Solar hydrogen panels

This section presents the cost structure of the components of the integrated solar hydrogen system. The direct cost of solar hydrogen panels is estimated at 260 €/m². This value is not a single assumed number, but the result of a bottom-up estimate based on the material and component costs listed in Section S7. In brief, the PV part of the panel is costed at 50 €/m², identical to the value assumed for separate PV modules, and the remaining 210 €/m² corresponds to the additional electrolysis-related components, assembly and manufacturing. Additional components contribute to the capital expenditure (CAPEX) of the solar hydrogen panels. The balance of module, which includes wiring, piping, electronics and mounting, adds a direct cost of 50 €/m². Indirect and owner costs add another 50 €/m².

Both the balance of module and the indirect and owner costs are based on the cost structure provided by [3] for solar hydrogen and are assumed to be similar to those of conventional solar panels. Working capital was estimated as 10 % of the combined direct and indirect costs. Contingency was estimated as 20 % of the same cost base. The assumptions on working capital and contingency were applied uniformly across all system components to ensure consistency in the CAPEX estimation.

Table S2 provides the CAPEX breakdown in thousand euros for solar hydrogen panels at three process capacities. CAPEX estimates for solar hydrogen panels do not account for scaling effects.

Table S2. CAPEX of solar hydrogen panels at the different installed capacities for the integrated solar hydrogen system (with and without intermediate hydrogen storage).

CAPEX - k€	**1k panels**		**100k panels**		**10M panels**	
	Without storage	With storage	Without storage	With storage	Without storage	With storage
Solar Hydrogen panels - direct cost	468	468	46,800	46,800	4,680,000	4,680,000
Balance of module - Direct cost	90	90	9,000	9,000	900,000	900,000
Indirect + Owners' costs	90	90	9,000	9,000	900,000	900,000
Working Capital	65	65	6,480	6,480	648,000	648,000
Contingency	130	130	12,960	12,960	1,296,000	1,296,000
Total	842	842	84,240	84,240	8,424,000	8,424,000

4.1.2. PV panels

For PV panels, the cost structure is similar to that presented for solar hydrogen panels. Direct costs include the cost of PV panels (50 €/m2) and the balance of module (50 €/m2). Indirect and owner costs represent an additional 50 €/m2 (based on [3]). Working capital and contingency were estimated as 10% and 20% of the total direct and indirect costs, respectively. Table S3 provides the CAPEX breakdown in k€ for PV panels at the three process capacities. CAPEX for PV panels does not include scaling effects.

Table S3. CAPEX of PV panels at the different installed capacities for the integrated solar hydrogen system (with and without intermediate hydrogen storage).

CAPEX - k€	**1k panels**		**100k panels**		**10M panels**	
	Without storage	With storage	Without storage	With storage	Without storage	With storage

PV panels - direct cost	6	9	632	770	63,166	77,032
Balance of module - Direct cost	6	9	632	770	63,166	77,032
Indirect + Owners' costs	6	9	632	770	63,166	77,032
Working Capital	2	3	189	231	18,950	23,109
Contingency	4	5	379	462	37,899	46,219
Total	25	35	2,463	3,004	246,346	300,423

4.1.3. Balance of Plant

The balance of plant consists of additional equipment required to operate the process under the correct conditions. In this case, it includes compressors, heat exchangers, mixers, gas liquid separators, dryer, deOxo unit, pumps, reverse osmosis, and ion exchange systems. Bare equipment costs were estimated in Aspen Economic Analyzer at different processing capacities (including an additional 10% to account for equipment delivery to the plant).

Direct and indirect costs were calculated by multiplying the sum of the equipment cost and the delivery cost by the factors described in Peters et al. [4], as shown in Table S4. Table S5 includes the bare equipment costs for the balance of plant. Table S6 presents the corresponding CAPEX.

Working capital and contingency were estimated as 10% and 20% of the sum of direct and indirect costs, respectively.

Table S4. Factors used to estimate direct and indirect cost of Balance of Plant components as a function of bare equipment cost. Based on [4]

Cost component	Factor of equipment cost (including delivery)
Direct Costs	
Purchased equipment installation	47%
Instrumentation & Controls(installed)	36%
Piping (installed)	68%
Electrical systems (installed)	11%
Buildings (including services)	18%
Yard improvements	10%
Service facilities (installed)	70%
Total Direct Costs	**260%**
Indirect costs	
Engineering and supervision	33%
Construction expenses	41%
Legal expenses	4%
Contractor's fee	22%
Total Indirect Costs	**100%**

Table S5. Bare equipment cost of the components of Balance of Plant for the integrated solar hydrogen system. Bare equipment cost estimated in Aspen Economic Analyzer V12.

	1k panels		**100k panels**		**10M panels**	
Equipment cost - k€	Without storage	With storage	Without storage	With storage	Without storage	With storage
Compressors	830	336	3,698	3,674	47,100	45,730
Heat exchangers	10	7	80	80	1,974	1,913
Mixers	44	44	89	89	1,300	1,297
Gas liquid separators	44	44	68	68	1,359	1,356
Dryer	8	8	50	50	4,960	4,948
DeOxo	29	29	567	565	5,465	5,459
Pumps	10	10	26	26	2,146	2,138
Reverse Osmosis	26	26	417	416	4,118	4,114
Ion Exchange	17	17	242	242	24,200	24,142
Total	1,019	521	5,236	5,210	92,622	91,098

Table S6. CAPEX of Balance of Plant at the different installed capacities for the integrated solar hydrogen system (with and without intermediate hydrogen storage).

CAPEX - k€	**1k panels**		**100k panels**		**10M panels**	
	Without storage	With storage	Without storage	With storage	Without storage	With storage
Balance of Plant - direct cost	2,913	1,491	14,974	14,899	264,900	260,539
Indirect + Owners' costs	1,120	573	5,759	5,731	101,885	100,207
Working Capital	403	206	2,073	2,063	36,678	36,075
Contingency	807	413	4,147	4,126	73,357	72,149
Total	5,243	2,683	26,953	26,819	476,820	468,971

4.1.4. Hydrogen Storage Tank

The CAPEX of the hydrogen storage tank was estimated using the same approach applied for the balance of plant CAPEX. Table S7 presents the bare cost of the hydrogen storage tank. Table S8 shows the corresponding CAPEX for hydrogen storage.

Table S7. Bare equipment cost of the components of hydrogen storage tank for the integrated solar hydrogen system.

	1k panels		100k panels		10M panels	
Equipment cost - k€	Without storage	With storage	Without storage	With storage	Without storage	With storage
Hydrogen Storage	0	25	0	199	0	18,830

Table S8. CAPEX of hydrogen storage tank at the different installed capacities for the integrated solar hydrogen system (with and without intermediate hydrogen storage).

CAPEX - k€	**1k panels**		**100k panels**		**10M panels**	
	Without storage	With storage	Without storage	With storage	Without storage	With storage
Hydrogen storage tank - direct cost	0	72	0	568	0	53,855
Indirect + Owners' costs	0	28	0	218	0	20,713
Working Capital	0	10	0	79	0	7,457
Contingency	0	20	0	157	0	14,914
Total	0	129	0	1,022	0	96,939

4.1.5. Battery

CAPEX for electricity storage batteries was estimated using cost data from [5]. Scaling effects and economies of scale were not included in the analysis. A specific CAPEX of 270 €/kWh was used [5]. Cost components such as direct costs, indirect and owner costs, working capital, and contingency were back calculated based on this figure. Working capital and contingency were estimated as 10% and 20%, respectively, of the sum of direct and indirect costs. Direct costs were estimated at 156 €/kWh, indirect and owner costs at 52 €/kWh, contingency at 42 €/kWh, and working capital at 21 €/kWh. Table S9 presents the CAPEX breakdown for batteries.

Table S9. CAPEX of Battery at the different installed capacities for the integrated solar hydrogen system (with and without intermediate hydrogen storage).

CAPEX - k€	**1k panels**		**100k panels**		**10M panels**	
	Without storage	With storage	Without storage	With storage	Without storage	With storage
Battery - direct cost	0	18	0	1,211	0	121,118
Indirect + Owners' costs	0	6	0	404	0	40,373
Working Capital	0	5	0	323	0	32,298
Contingency	0	2	0	161	0	16,149
Total	0	31	0	2,099	0	209,938

4.1.6. Aggregation

The CAPEX values provided in the tables above can be combined into a single total CAPEX. Table S10 presents the total CAPEX for the integrated solar hydrogen system.

Table S10. CAPEX breakdown for the integrated solar hydrogen system, with and without intermediate hydrogen storage, at different processing capacities.

CAPEX - k€	**1k panels**		**100k panels**		**10M panels**	
	Without storage	With storage	Without storage	With storage	Without storage	With storage
Balance of Plant – Direct costs	2,913	1,491	14,974	14,899	264,900	260,539
Solar Hydrogen panels – direct cost	468	468	46,800	46,800	4,680,000	4,680,000
Balance of module Solar H. Panels- Direct cost	90	90	9,000	9,000	900,000	900,000
PV Panels – direct cost	6	9	632	770	63,166	77,032
Balance of module PV Panels- Direct cost	6	9	632	770	63,166	77,032
Hydrogen Storage Tank - Direct cost	0	72	0	568	0	53,855
Battery – Direct cost	0	18	0	1,211	0	121,118
Indirect + Owners' costs	1,217	706	15,391	16,123	1,065,050	1,138,325
Working Capital	470	289	8,743	9,176	703,628	746,939
Contingency	940	570	17,486	17,867	1,407,256	1,445,431
Total	6,110	3,721	113,657	117,185	9,147,166	9,500,272
Total - M€	6.1	3.7	113.7	117.2	9,147.2	9,500.3

4.2. PV-E system

4.2.1. PV panels

The CAPEX structure of the PV panels in the PV-E system is similar to that of the integrated solar hydrogen system, but the function of the PV panels differs. In the PV-E system, PV panels provide electricity for both hydrogen production and the balance of plant. In contrast, in the integrated solar hydrogen system, hydrogen is produced directly in the solar hydrogen panels, and the PV panels are only used to supply electricity to the balance of plant. As a result, the total installed PV capacity and associated CAPEX are higher in the PV-E system (see Table S11).

Table S11. CAPEX of PV panels at the different installed capacities for the PV-E system (with and without intermediate electricity storage).

CAPEX - k€	1k panels		100k panels		10M panels	
	Without storage	With storage	Without storage	With storage	Without storage	With storage
PV panels - direct cost	96	100	9,632	10,013	963,166	962,219
Balance of module - Direct cost	96	100	9,632	10,013	963,166	962,219
Indirect + Owners' costs	96	100	9,632	10,013	963,166	962,219
Working Capital	29	30	2,889	3,004	288,950	288,666
Contingency	58	60	5,779	6,008	577,899	577,331
Total	376	389	37,563	39,050	3,756,346	3,752,653

4.2.2. Balance of plant

The cost structure of the balance of plant in the PV-E system is analogous to that of the integrated solar hydrogen system. However, the absolute CAPEX values may differ due to differences in process configuration and system sizing. This is particularly the case when electricity storage is included in the PV-E system. In comparison, the integrated solar hydrogen system includes hydrogen storage instead, which affects the sizing and cost distribution of the balance of plant. Table S12 includes the bare equipment costs for the balance of plant. Table S13 presents the corresponding CAPEX.

Table S12. Bare equipment cost of the components of Balance of Plant for the PV-E system. Bare equipment cost estimated in Aspen Economic Analyzer V12.

	1k panels		100k panels		10M panels	
Equipment cost - k€	Without storage	With storage	Without storage	With storage	Without storage	With storage
Compressors	830	340	3,698	2,235	47,100	22,224
Heat exchangers	10	4	80	43	1,974	777
Mixers	44	18	89	54	1,300	574
Gas liquid separators	44	18	68	46	1,359	561
Dryer	8	3	50	27	4,960	1,853
DeOxo	29	12	567	193	5,465	3,020
Pumps	10	4	26	18	2,146	483
Reverse Osmosis	26	11	417	186	4,118	2,201
Ion Exchange	17	7	242	104	24,200	9,041
Total	830	340	3,698	2,235	47,100	22,224

Table S13. CAPEX of Balance of Plant at the different installed capacities for the PV-E system (with and without intermediate electricity storage).

CAPEX - k€	1k panels	100k panels	10M panels

	Without storage	With storage	Without storage	With storage	Without storage	With storage
Balance of Plant - direct cost	2,913	1,193	14,974	8,311	264,900	116,499
Indirect + Owners' costs	1,120	459	5,759	3,197	101,885	44,807
Working Capital	403	165	2,073	1,151	36,678	16,131
Contingency	807	330	4,147	2,301	73,357	32,261
Total	5,243	2,148	26,953	14,960	476,820	209,698

4.2.3. Battery

The cost structure of the battery system in the PV-E configuration is analogous to that of the battery in the integrated solar hydrogen system. However, the absolute CAPEX values may differ due to differences in storage requirements, system sizing, and operating conditions (see Table S14). In the PV-E system, electricity is stored in batteries to supply both the hydrogen production unit and the balance of plant. In contrast, in the integrated solar hydrogen system, batteries are only used to cover the electricity demand of the balance of plant.

Table S14. CAPEX of Battery at the different installed capacities for the PV-E system (with and without intermediate electricity storage).

CAPEX - k€	**1k panels**		**100k panels**		**10M panels**	
	Without storage	With storage	Without storage	With storage	Without storage	With storage
Battery - direct cost	0	315	0	30,646	0	2,712,577
Indirect + Owners' costs	0	105	0	10,215	0	904,192
Working Capital	0	84	0	8,172	0	723,354
Contingency	0	42	0	4,086	0	361,677
Total	0	546	0	53,119	0	4,701,800

4.2.4. Electrolyzer

As part of the direct cost for the electrolyzer, an amount of 900 €/kW was used based on the descriptions provided in [6]. Indirect and owner costs were estimated as 485 €/kW based on the cost descriptions from [6]. Working capital was estimated as 10% of the sum of direct and indirect costs. Contingency was estimated as 20% of the same sum. Table S15 presents the CAPEX breakdown in k€ for the three process capacities. The CAPEX for electrolyzers does not account for scaling effects.

Table S15. CAPEX of electrolyzer at different installed capacities for the PV E system (with and without intermediate electricity storage).

CAPEX - k€	**1k panels**		**100k panels**		**10M panels**	
	Without storage	With storage	Without storage	With storage	Without storage	With storage
Electrolyzer - direct cost	406	123	40,584	12,835	4,058,392	1,516,752
Indirect + Owners' costs	219	66	21,853	6,911	2,185,286	816,712
Working Capital	62	19	6,244	1,975	624,368	233,346
Contingency	125	38	12,487	3,949	1,248,736	466,693

Total	812	246	81,168	25,671	8,116,781	3,033,504

4.2.5. Aggregation

The CAPEX values shown in the tables above can be combined into a single total CAPEX figure. Table S16 presents the total CAPEX for the integrated solar hydrogen system.

Table S16. CAPEX breakdown for the PV-E system with and without intermediate hydrogen storage at different processing capacities.

CAPEX - k€	**1k panels**		**100k panels**		**10M panels**	
	Without storage	With storage	Without storage	With storage	Without storage	With storage
Balance of Plant – Direct costs	2,913	1,193	14,974	8,311	264,900	116,499
PV Panels – direct cost	96	100	9,632	10,013	963,166	962,219
Balance of module PV Panels- Direct cost	96	100	9,632	10,013	963,166	962,219
Electrolyzer – Direct cost	406	123	40,584	12,835	4,058,392	1,516,752
Battery – Direct cost	0	315	0	30,646	0	2,712,577
Indirect + Owners' costs	1,435	730	37,244	30,336	3,250,336	2,727,930
Working Capital	495	298	11,207	14,301	949,996	1,261,496
Contingency	989	470	22,413	16,345	1,899,992	1,437,962
Total	6,431	3,330	145,685	132,800	12,349,947	11,697,654
Total - M€	6.4	3.3	145.7	132.8	12,349.9	11,697.7

Figure S5 shows that adding intermediate electricity storage reduces CAPEX by half for a 1 k panel plant (48 %). This reduction occurs mainly because of the smaller size of the electrolyzer and compressors. At larger scales (100 k and 10 M panels), the absolute CAPEX also decreases (9 % and 5 %, respectively). However, the savings become modest because battery costs rise significantly, becoming the largest single expense (~23 % of total). As the plant size increases, the relative importance of balance of plant costs, including compressors, decreases from 45 % to below 2 %. In contrast, costs related to the electrolyzer without storage or electrolyzer plus battery with storage dominate. Thus, at large scales, the additional operating hours provided by storage nearly, but not fully, offset the increased battery CAPEX, resulting in only a small overall CAPEX reduction.

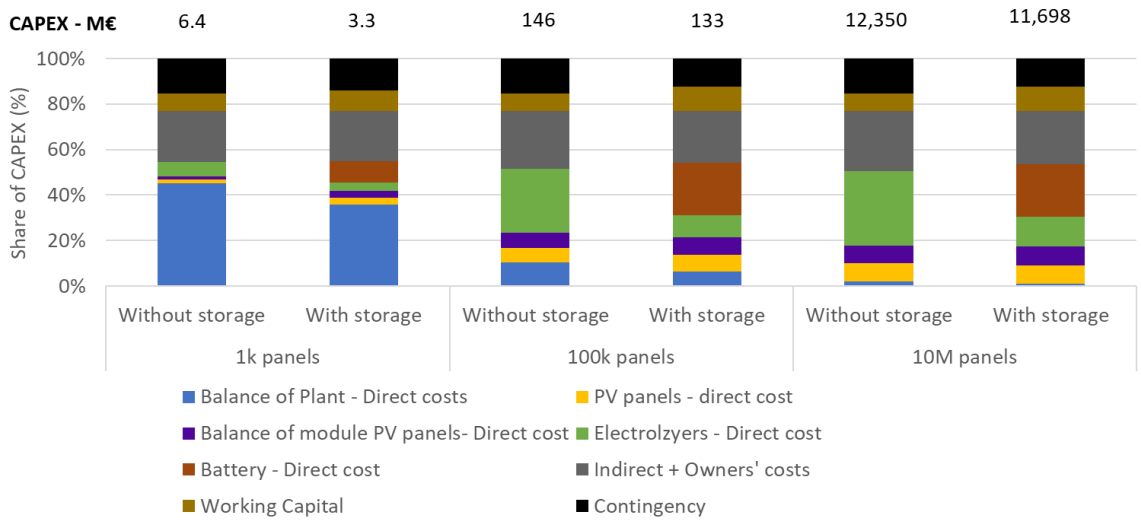


Figure S5. Total capital investments and cost distribution for a detached PV-E plant for hydrogen production at the different installed capacities (with and without intermediate electricity storage).

5. Hydrogen production cost

This section focuses on presenting the LCOH of the PV-E system and providing extra information on the effect of hydrogen delivery pressure for both systems

5.1. LCOH of PV-E system

Figure S6 illustrates a clear scale effect. For a system with 1k panels, intermediate electricity storage reduces the levelized cost of hydrogen by nearly half, from 51.6 to 28.2 €/kg. This occurs because the battery allows longer daily operation, enabling the use of smaller electrolyzers and compressors. At 100k panels, this benefit nearly disappears, with only a 3 % cost reduction. At 10 million panels, adding a battery slightly increases the cost. This happens because compressor and other balance-of-plant costs diminish as system scale increases, while battery capital expenditure grows almost linearly with installed photovoltaic capacity.

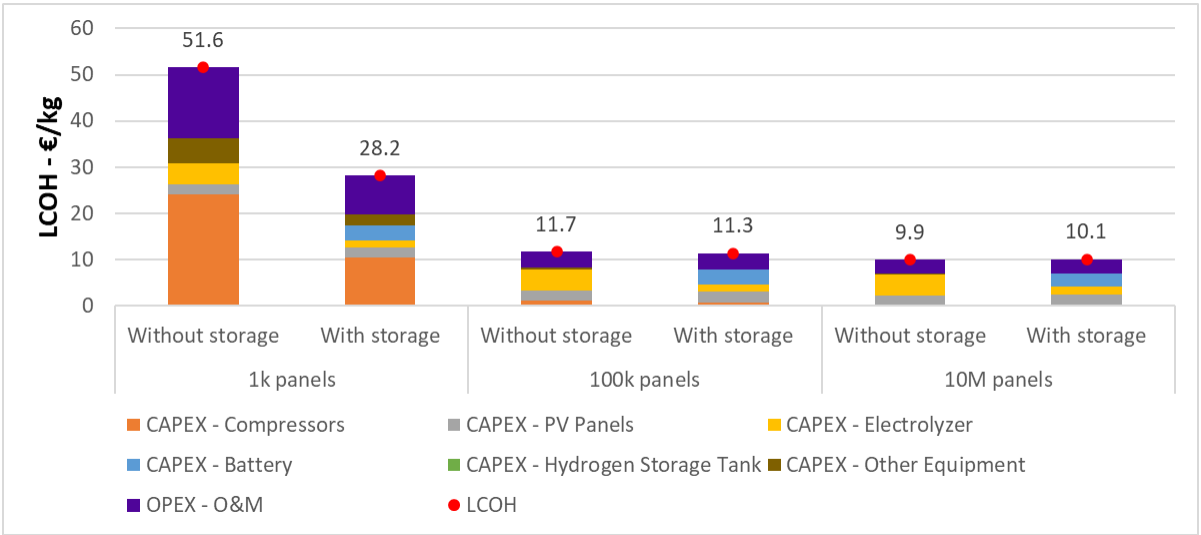


Figure S6. Levelized cost of hydrogen production using a detached PV-E system at different system capacities (without and with storage).

5.2. Effect of Hydrogen Delivery Pressure on LCOH

The results presented here show that the trend for both systems is analogous, with the effect of delivery pressure being larger for small scale systems. Figure S7 shows the effect of pressure on LCOH for all capacities for system 1, while Figure S8 shows the of pressure on LCOH for all capacities for system 2. For System 2, trends are similar to those observed for System 1. However, even if the cost of compression is eliminated at a delivery pressure of 10 bar, other assets, such as electricity storage and the impact of additional equipment, become significant. Despite these adjustments, at 10 bar, the cost of hydrogen remains higher than the target of €5 per kg for competitiveness with fossil hydrogen.

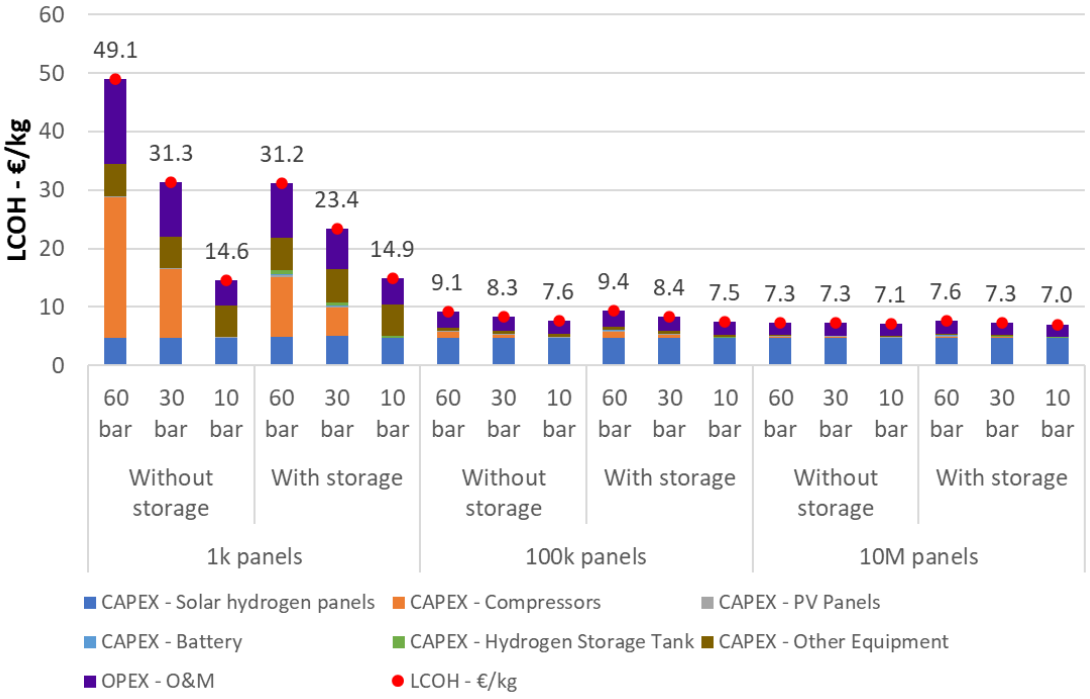


Figure S7. Levelized cost of hydrogen at different hydrogen delivery pressures for System 1.

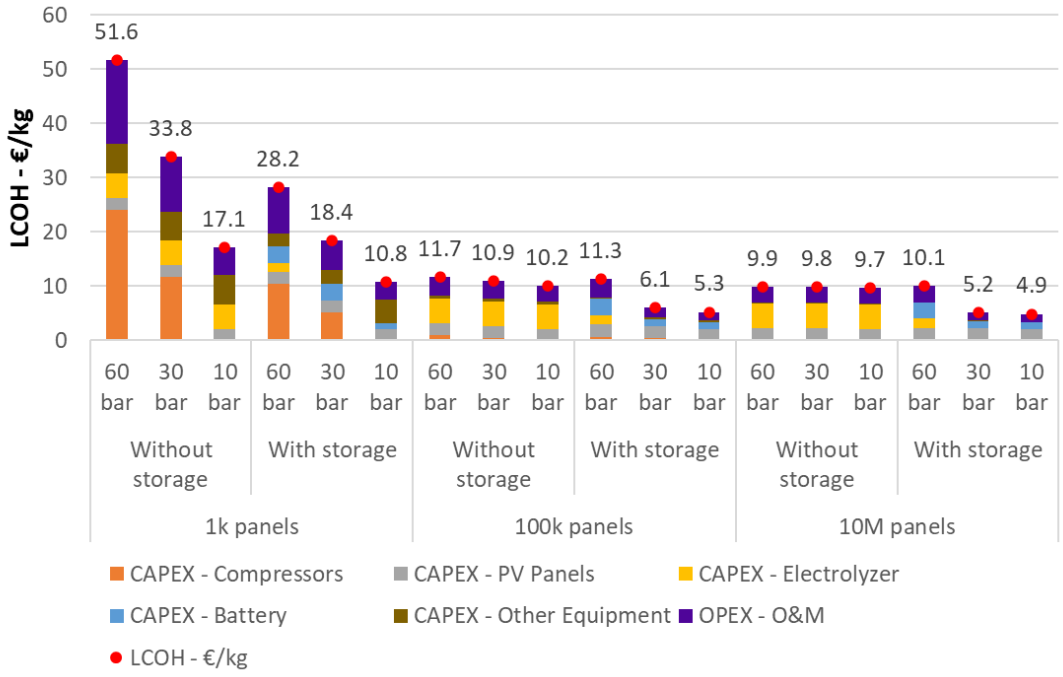


Figure S8. Levelized cost of hydrogen at different hydrogen delivery pressures for System 2.

6. Sensitivity analysis

This section presents the results of sensitivity analysis for the case when intermediate storage is considered for system 1 and the sensitivity analysis results for system 2.

6.1. Integrated solar hydrogen panels system

Figure S9 shows the results of sensitivity analysis of LCOH for a 100,000 solar hydrogen panel system with storage.

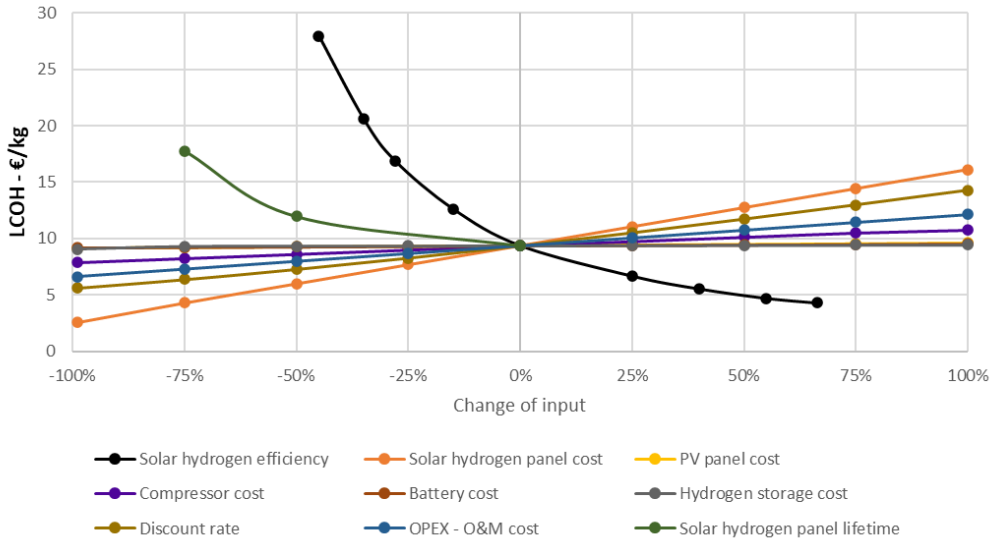


Figure S9. Sensitivity analysis of LCOH to change in input parameters for a 100,000 solar hydrogen panel system with storage.

6.2. PV-E system

Figure S10 shows the results of the sensitivity analysis for System 2 with 100,000 panels. The parameter with the largest impact on the LCOH is the electrolyzer efficiency. Any decrease in efficiency notably increases the hydrogen cost. Lower PV panel efficiency also raises the cost, but its effect is smaller compared to the electrolyzer efficiency. Another important parameter is the electrolyzer CAPEX. Reducing this cost significantly decreases the LCOH. In contrast, changes in compressor CAPEX and PV panel CAPEX follow a similar trend but have a smaller influence than the previously discussed parameters. Still, lowering these costs would help decrease hydrogen production costs.

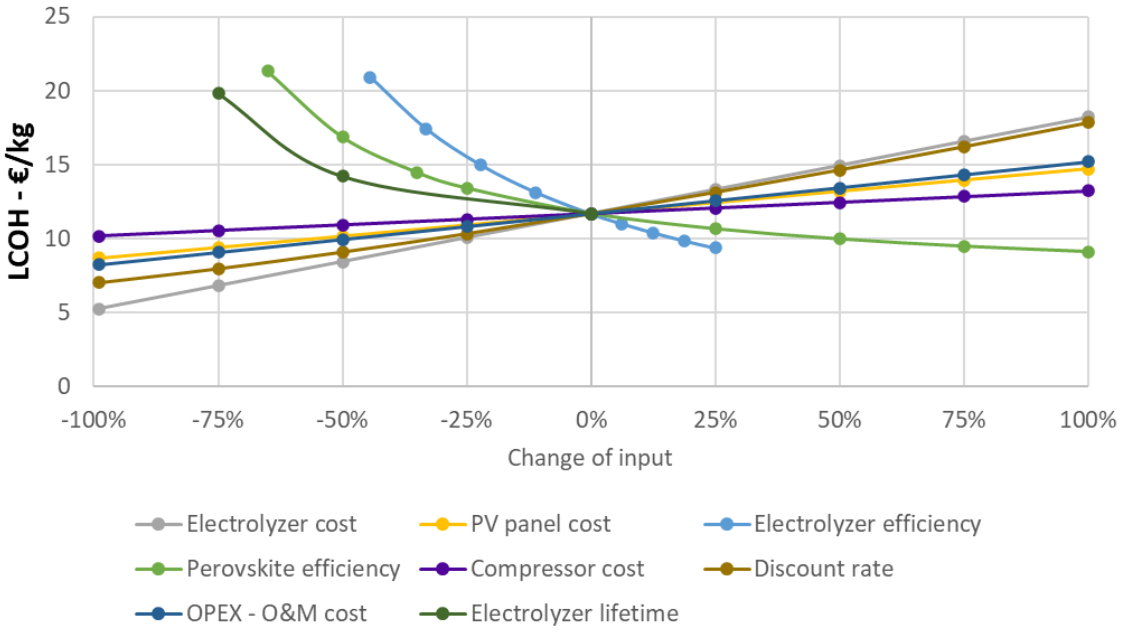


Figure S10. Sensitivity analysis of LCOH to change in input parameters for a 100,000 PV-E system without storage.

When storage is included in the system (Figure S11), electrolyzer efficiency remains the factor with the greatest impact on LCOH, similar to what is observed without storage. A counterintuitive result appears for PV-panel efficiency. Increasing panel efficiency, while keeping all other inputs constant, slightly raises the overall cost. This happens because higher peak power requires a larger battery to smooth out fluctuations, and the added battery CAPEX outweighs the small savings from reducing panel area. Battery cost itself becomes the second most important factor. Cuts of 50% or more lead to a noticeably larger drop in LCOH compared to similar percentage changes in any other cost. Therefore, beyond electrolyzer efficiency, significant cost reductions depend more on lowering battery prices than on further improving PV-panel efficiency.

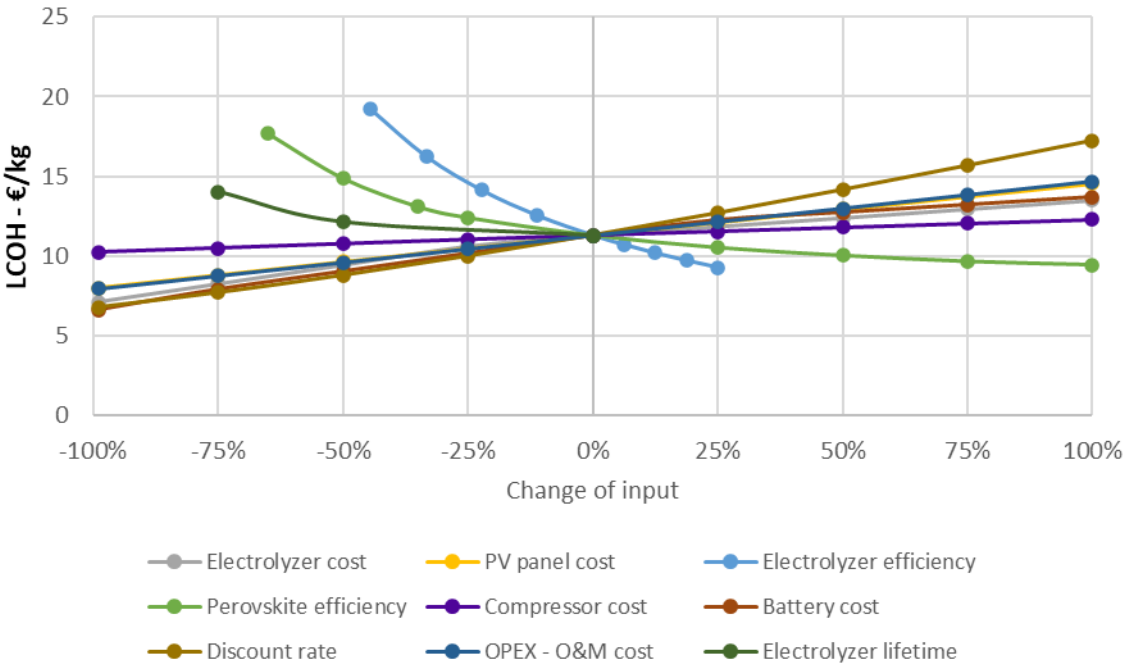


Figure S11. Sensitivity analysis of LCOH to change in input parameters for a 100,000 PV-E system with storage.

7. Cost components of integrated solar hydrogen panels

This section presents an indicative cost breakdown of an integrated solar hydrogen panel used in the calculations. Various designs and combinations of materials can be selected to produce solar hydrogen panels. Providing detailed cost estimates requires specific design choices that are beyond the scope of this analysis. Therefore, the following breakdown is intentionally general and offers only a rough estimate of the panel costs. As such, it can accommodate different types of integrated solar hydrogen panel designs, for example, those based on photovoltaic and electrolyzer materials or those employing novel photoelectrode materials. The total panel costs in this analysis are higher than those estimated in previous studies [7, 8]. However, the panels analyzed here operate at a higher efficiency of 18% compared to 10% in previous references. The effect of varying solar hydrogen panel costs is explored through sensitivity analysis. The cost term of 150 €/m² assigned to the electrolysis components in Table S17 includes flow plates, porous transport layers, the membrane and the (noble-)metal catalysts in the integrated panel. Typical ranges of iridium and platinum loadings reported for PEM water electrolyzers, in combination with metal prices in 2023, indicate that the noble-metal contribution represents only part of this term, with the remainder coming from other stack materials. This implies that even relatively large fluctuations in iridium and platinum prices would lead to more modest changes in total panel CAPEX than the ±50 % range explored in the sensitivity analysis.

Table S17. Indicative cost breakdown of solar hydrogen panels

Solar hydrogen panel component	Indicative component elements	Costs - (€/m²)	Reference
Photoactive components	Glass	50	Own estimate, based on existing costs of PV materials plus a premium for higher efficiency tandem approach [3].
	Photoactive layer		

	Conductive layers		
Electrolysis components	Flow/ endplates	150	Own estimate, based on material costs.
	PTL Cathode/ Anode		
	Catalyst materials		
	Membrane		
Other components		30	Assumption
Manufacturing and assembly		30	Assumption
Total solar hydrogen panel cost (€/m^2)		**260**	

References

1. JRC, *Joint Research Centre - Photovoltaic Geographical Information System (PVGIS).* Avalailable at: https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis_en, 2023. **Accessed June 18, 2023**.
2. Bhandari, R. and R.R. Shah, *Hydrogen as energy carrier: Techno-economic assessment of decentralized hydrogen production in Germany.* Renewable Energy, 2021. **177**: p. 915-931.
3. Jäger-Waldau, A., *PV Status Report 2019.* EUR 29938 EN, 2019. **Publications Office of the European Union**(Luxembourg, ISBN 978-92-76-12608-9).
4. Peters, M.S., K.D. Timmerhaus, and R.E. West, *Plant design and economics for chemical engineers*. Vol. 4. 2003: McGraw-Hill New York.
5. Lazard, *Lazard's Levelized Cost of Energy Analysis—Version 16.0.* 2023.
6. Eblé, L. and M. Weeda, *Evaluation of the levelised cost of hydrogen based on proposed electrolyser projects in the Netherlands. Renewable Hydrogen Cost Element Evaluation Tool (RHyCEET).* TNO report R10766, 2024.
7. Shaner, M.R., et al., *A comparative technoeconomic analysis of renewable hydrogen production using solar energy.* Energy & Environmental Science, 2016. **9**(7): p. 2354-2371.
8. Pinaud, B.A., et al., *Technical and economic feasibility of centralized facilities for solar hydrogen production via photocatalysis and photoelectrochemistry.* Energy & Environmental Science, 2013. **6**(7): p. 1983-2002.