TECHNO-ECONOMIC EVALUATION FOR JOINT PRODUCTION OF ELECTRICITY AND GREEN HYDROGEN WITH HYBRID CONCENTRATED SOLAR POWER (CSP) AND PHOTOVOLTAIC (PV) TECHNOLOGIES COUPLED WITH PEM ELECTROLYZERS

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Abstract

A techno-economic analysis is conducted on integrating PEM electrolyzers and solar power plants, including a Concentrated Solar Power (CSP) and Photovoltaic (PV) plant in northern Chile. The methodological approach is based on production analysis through four alternatives: PV and PEM (Case 1), CSP and PEM (Case 2), a hybrid case of CSP, PV, and PEM (Case 3), and the same hybrid case but with a higher capacity PEM plant (Case 4). SAM software is used to create solar plant models, while Python is used to model the PEM electrolysis plant and perform system integration. The economic evaluation aims to calculate the levelized cost of electricity (LCOE) and the levelized cost of hydrogen (LCOH). Results yield a minimum LCOH of 5,76 USD/kg H_2 and a maximum of 6,63 USD/kg H_2 for the current scenario (2024), while for the future scenario (2030), values range between 2,86 and 4,26 USD/kg H_2. The configuration that achieved the lowest LCOE and LCOH was Case 1. In all evaluated cases, green hydrogen production costs exceed 2 USD/kg H_2, both in the current and future scenarios. Therefore, green hydrogen is not economically competitive with gray hydrogen under these conditions. However, as electricity prices and electrolyzer investment costs decrease, and efficiency improves, green hydrogen could become competitive. These results provide valuable insights for decision-making regarding solar hydrogen production policies.

Keywords: PEM electrolyzer, CSP, PV, LCOE, LCOH, hydrogen.

1. Introduction

Green hydrogen emerges as a prominent energy vector to contribute to the decarbonization of the planet [1]–[3], and Chile positions itself with the potential to lead its production thanks to its abundant solar resources [4], [5]. However, the cost of hydrogen produced using solar energy remains high due to high investment costs, limited operating hours, and the price of solar energy itself [6].

To harness solar energy, there are two main types of solar technologies: photovoltaic (PV) solar plants and concentrated solar power (CSP) plants. The former has a low investment cost, but its production is intermittent and limited by fluctuations in solar resources. One solution is electrical energy storage, though this comes with high investment costs. On the other hand, a CSP plant can incorporate a thermal energy storage (TES) system at a lower cost, allowing for controlled energy dispatch and a higher capacity factor. A hybrid CSP and PV plant has the advantage of achieving a high capacity factor, where the PV plant operates during sunlight hours, while the CSP plant stores the generated thermal energy for use when solar radiation is not available, thus mitigating the effects of variability in solar production under intermittent conditions.

Currently, global hydrogen production has reached 95 Mton H_2/year, with 83% of this being produced from fossil fuels, followed by production via oil and gasoline reforming at 16%. This type of hydrogen is referred to as grey hydrogen and emits approximately 1,2 Mton CO_2/year [2]. Carbon-free hydrogen production accounts for only 0,7% of total production [3]. This carbon-free hydrogen can be obtained through electrolysis. PEM (Polymer Electrolyte Membrane) electrolyzers use an electrolyte composed of a thin polymer membrane, which facilitates the conduction of hydrogen protons (H+) due to its composition of sulfonic acid functional groups (−SO3OH). This membrane is notable for its high efficiency, high oxidative stability, and good durability [7]. PEM electrolyzers are capable of operating at much higher current densities compared to alkaline electrolyzers; however, these high current densities

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require very specific materials such as platinum, iridium, and ruthenium, which increase production costs [8]. On the other hand, when coupled with a renewable energy source, PEM electrolyzers exhibit a good dynamic response to fluctuations in electrical supply [9], which is not observed with other types of electrolyzers

In recent years, several studies have been published on hydrogen production using solar energy. These research works evaluate three main electrolysis technologies: alkaline, proton exchange membrane (PEM), and solid oxide. Regarding the associated solar technology, photovoltaic (PV) technology is the most commonly used, closely followed by concentrated solar power (CSP). In this context, Rosenstiel et al. [10] evaluated hydrogen production via a hybrid (CSP-PV) plant with an alkaline electrolyzer, obtaining an LCOH of 4,04 USD/kg H2 for Morocco, a location with an annual direct normal irradiation of 2518 kWh/m^2. Moraga et al. [11] evaluated three configurations: CSP, PV, and CSP-PV in northern Chile, with an annual direct normal irradiation of 3000 kWh/m^2. The results showed that the LCOH reaches its minimum value for the PV-ALK configuration, with a value of 2,38 USD/kg H_2. Grube et al. [12] studied hydrogen production using four technologies: CSP/PEM, CSP/SOE, PV/PEM, and PV/SOE. The results indicated that the minimum LCOH is obtained with the CSP/SOEC configuration, with a value of 5,02 USD/kg H_2. Gallardo et al. [4] evaluated CSP and PV technologies separately with PEM and ALK electrolyzers, with these plants located in the Atacama Desert. The minimum LCOH obtained was 2,2 USD/kg H_2 with the PV-ALK technology. On the other hand, Yang et al. [13] proposed a model for the PV-PEM electrolysis system, detailing the voltage-current characteristics of both the PV cell and the PEM electrolyzer. Tebibel et al. [14] compared hydrogen production using PV technology through three electrolysis processes: PEM, methanol, and hybrid sulfur. Gallardo et al. [15] proposed a methodology for the optimal sizing of grid-connected PV-PEM systems, with results ranging between 5,9 and 11,3 USD/kg H_2. Xiang et al. [16] evaluated the LCOH for PV and nuclear technology in China, showing that by 2050, the PV-PEM technology could achieve an LCOH of 0,1154 USD/kg H_2. Nasser et al. [17] studied hydrogen production using different pathways: PV, wind, and a Rankine cycle with waste heat, obtaining an LCOH of 6,45 USD/kg H_2 for the PV case. Bhandari et al. [18] obtained an LCOH of 6,79 USD/kg H2 and 8,57 USD/kg H_2 for the PV-ALK and PV-PEM cases, respectively, for a global radiation of 3,23 kWh/m^2/day. Rezaei et al. [19] examined the sensitivity of LCOH produced by a PV plant, demonstrating the importance of careful site selection to achieve a high PV capacity factor. Finally, Jaradat et al. [20] discussed the potential for green hydrogen production in Jordan through a PV solar system using ALK and PEM

In summary, some articles have focused on the design of integrated systems using optimization functions to achieve the minimum Levelized Cost of Hydrogen (LCOH) [10], [15], while others have considered the design of CSP and PV plants using fixed design capacities [11], [12], [16], [21]. This study evaluates the integration of solar power generation technologies, CSP and/or PV, coupled with a PEM electrolyzer, operating in off-grid mode, to produce green hydrogen in a region with high solar radiation

2. Methodology

Green hydrogen production through solar energy is evaluated in northern Chile, one of the regions with the highest solar irradiance in the world. CSP and PV power plants are configured, along with PEM electrolyzers, which are modeled using specialized software to obtain the hourly annual production of each output. Subsequently, the levelized costs of electricity and hydrogen are calculated, and the main variables are analyzed for sensitivity to determine the optimal configuration. Two scenarios are evaluated: one for the present (2024) and one for the future (2030).

Three configurations (Figure 1) were modeled and evaluated considering four analysis alternatives. The first configuration, Case 1, includes PV and PEM; the second configuration, Case 2, involves CSP and PEM; the third configuration, Case 3, is a hybrid system comprising CSP, PV, and PEM; and finally, Case 4 is the same hybrid configuration (CSP, PV, and PEM) but with a higher capacity PEM plant.

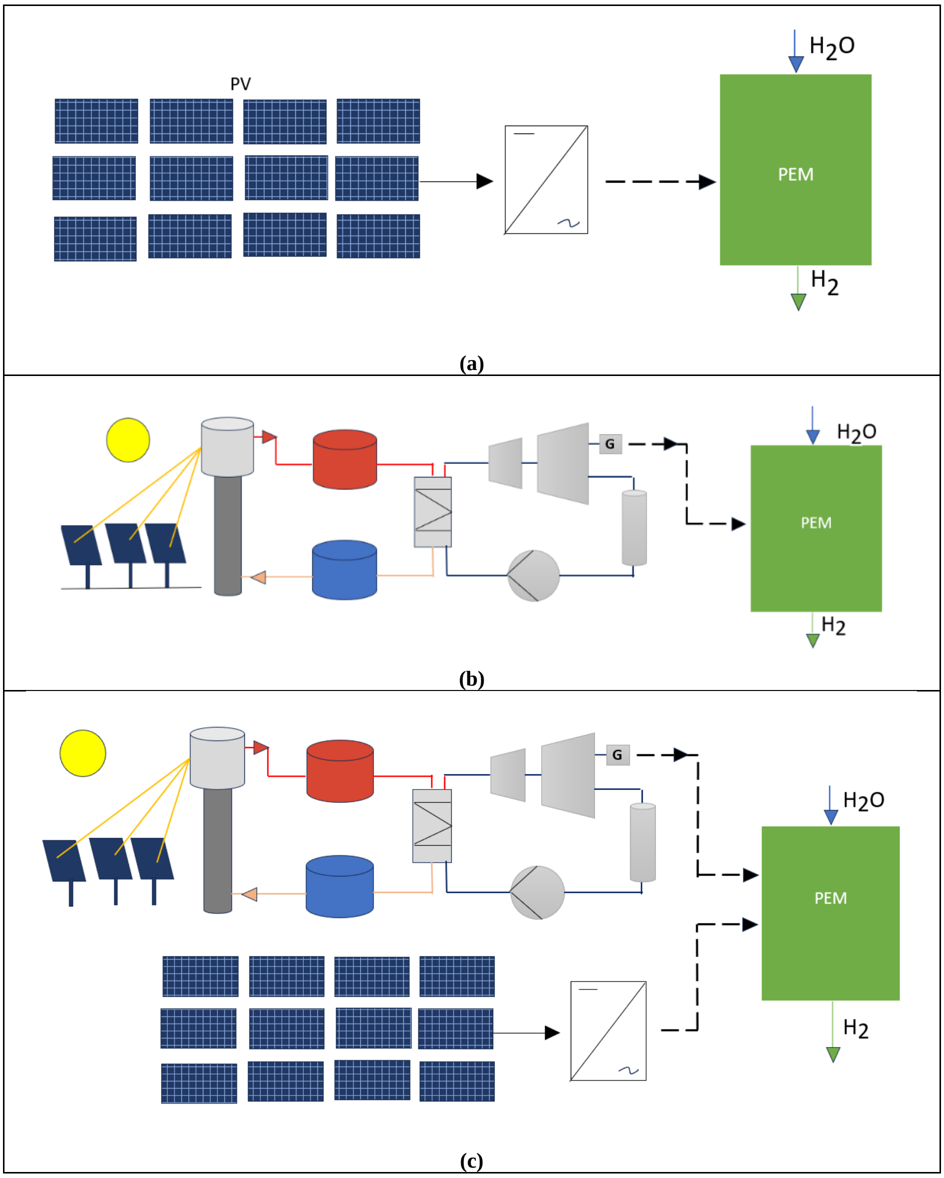


Fig. 1: Configurations evaluated a) PV and PEM, b) CSP and PEM. c) hybrid plant (CSP, PV and PEM)

SAM software [22] is used for modeling solar plants (CSP and PV), while Python programming language [23] is utilized for modeling PEM electrolysis plants and model integration, to determine the annual hourly production of electricity and hydrogen. The economic evaluation aims to calculate the levelized cost of energy (LCOE) and the levelized cost of hydrogen (LCOH). Two temporal scenarios are considered, a current scenario and a future one.

The location of the plants under evaluation is in the Antofagasta region of northern Chile (22,81 °S, 69,51 °W), at 1525 meters above sea level, 3 kilometers from “Atacama I / Cerro Dominador” [24]. This site has high irradiation levels: 3724 kWh/(m² year) of direct normal irradiation and 2580 kWh/(m² year) of global horizontal irradiation [5]. This site is chosen due to its high radiation values, making it an attractive location for evaluating a new CSP and PV project in the area

Design and Modeling of the CSP and PV System. The modeled CSP plant has a nominal capacity of 19,9 MW, with 15 hours of TES, a solar multiple of 2,5, 2625 heliostats of 118,8 m², a 140 m tower, an 8,89 m receiver, operating with HTF at 565 °C, and an evaporative-type condenser. The PV plant, on the other hand, has a nominal capacity of 20 MW, with 81840 Yingli Solar YL245-29b modules, 20 inverters with 98,5% efficiency, and a capacity of 500 kWac.

The PEM electrolyzer was modeled using the methodology outlined in [25], where the hydrogen flow at the outlet is determined using Equation 1

$$\dot{N}_{H2out} = \frac{J}{2 \cdot F} \qquad \text{(eq. 1)}$$

where J is the density current density and F is the Faraday constant.

The power consumed by the electrolyzer is determined by Equation 2

$$W = I \cdot n_{cell} \cdot V_{cell} \qquad \text{(eq. 2)}$$

where I is the current consumed by the electrolyzer, n_{cell} is the number of cells, and V_{cell} is the cell voltage.

The cell voltage is calculated by Equation 3

$$V_{cell} = V_0 + V_{act} + V_{ohm} \qquad \text{(eq. 3)}$$

where V_0 is the reversible voltage, V_{act} is the activation voltage y V_{ohm} is the ohmic overpotential.

Finally, the efficiency of the electrolyzer is calculated with Equation 4.

$$\eta_{PEM} = \frac{\dot{N}_{H2out} \cdot HHV_{H2}}{W} \qquad \text{(eq. 4)}$$

where HHV_{H2} is the higher heating value of hydrogen.

In Cases 1, 2, and 3, an 18 MW electrolyzer was considered, whereas in Case 4, a 35 MW electrolyzer was used.

The parameters employed in the PEM cell model are presented in Table 1.

Tab. 1: Main parameters used in the PEM cell model [25].

Parameter	Value	Unit
Operating pressure	1,0	Atm
Operating temperatura	353	K
Reference Temperature	298,15	K
Anode activation energy	76	kJ/mol
Cathode activation energy	18	kJ/mol
Water content at the anode membrane interface	14	-
Water content at the cathode membrane interface	10	-
Membrane thickness	100	μm
Specific electrical consumption	54	kWh/kg H_2

For hydrogen compression, the energy required to store the produced hydrogen was determined using Equation 5.

$$L_{e,spec} = \frac{C_{pH2} \cdot \Delta T_{12}}{\eta_m \cdot \eta_e} = \frac{T_1 \cdot \left(\beta^{\frac{k-1}{k}} - 1\right)}{\eta_m \cdot \eta_e} \qquad \text{(eq. 5)}$$

where $L_{e,spec}$ is the specific electrical consumption for the compression, C_{pH2} is the specific heat of hydrogen, T_1 and T_2 are the input and output temperatures respectively, η_m y η_e are the mechanical and electrical efficiency correspondingly, β is the compression ratio, and k is the isentropic coefficient. Mechanical and electrical efficiency are considered to be 70% and 90% respectively [4], and hydrogen is compressed from 20 bar to 350 bar.

The Levelized Cost of Energy (LCOE) represents the total cost of constructing and operating a power plant, divided by the total energy production over the plant's evaluation period. It is determined using Equation 6.

$$LCOE = \frac{CAPEX + \sum_{i=1}^{n} \frac{OPEX_i}{(1+t)^i}}{\sum_{i=1}^{n} \frac{E_i \cdot (1-d)^i}{(1+t)^i}} \qquad \text{(eq. 6)}$$

where $CAPEX$ is the investment cost, $OPEX$ is the operational cost, n is the evaluation period, t is the disount rate, E_i is the annual energy production, and d is the annual degradation factor.

The LCOE of a hybrid CSP and PV plant is obtained by Equation 7 [26]

$$LCOE_{HYB} = \frac{LCOE_{PV} \cdot E_{PV} + LCOE_{CSP} \cdot E_{CSP}}{E_{PV} + E_{CSP}} \quad \text{(eq. 7)}$$

The Levelized Cost of Hydrogen (LCOH) represents the average cost of hydrogen production, accounting for both capital and operational expenses. It is calculated by Equation 8

$$LCOH = \frac{CAPEX + \sum_{i=1}^{n} \frac{OPEX_i}{(1+t)^i}}{\sum_{i=1}^{n} \frac{H_i \cdot (1-d)^i}{(1+t)^i}} = \quad \text{(eq. 8)}$$

where H_i is the annual production of hydrogen.

Tables 2, 3, and 4 present the cost structures of the evaluated plants (CSP, PV, and PEM), respectively. These data were used to conduct the economic evaluations.

Tab. 2: Cost structure of the CSP plant [6], [22], [27]

Costs	Parameter	Value (2024)	Value (2030)	Unit
Direct	Site improvements	16	10	USD/m^2
	Heliostat field	122	50	USD/m^2
	Solar tower	95.000	75.000	USD/m
	receiver	39.335.054	28.711.717	USD
	TES (Thermal Energy Storage)	22	10	USD/kWh
	Power block	1.100	700	USD/kW
	Balance of plant	340	340	USD/kW
	Contingency	5	2	%
Indirect	EPC (Engineering, procurement, and construction)	10	10	%
O&M	Fixed costs	66	66	USD/kW
	Variable costs	3,5	3,5	USD/MWh

Tab. 3: Cost structure of the PV plant [22], [28]–[30]

Costs	Parameter	Value (2024)	Value (2030)	Unit
Direct	Modules	0,3	0,17	USD/W$_{dc}$
	Investors	0,05	0,05	USD/W$_{ac}$
	Balance of plant	0,27	0,15	USD/W$_{dc}$
	Installation	0,11	0,11	USD/W$_{dc}$
	Contingency	3	1	%
Indirect	EPC	0,08	0,08	USD/W$_{dc}$
O&M	Fixed costs	15	8,1	USD/kW/year

Tab. 4: Cost structure of PEM plant [4], [31], [32]

Element	Parameter	Value (2024)	Value (2030)	Unit
PEM	CAPEX	1.100	650	USD/kW
	Stack replacement	65.000	90.000	h
Compressor	$CAPEX_{Comp}$	3.900	3.900	USD/kW
	$OPEX_{Comp}$	4	4	% $CAPEX_{Comp}$
Storage	$CAPEX_{Storage}$	500	500	USD/kg H_2
	$OPEX_{Storage}$	2	2	% $CAPEX_{Storage}$
EPC & O&M	$CAPEX_{EPC}$	3	3	% $CAPEX$

The economic parameters used for calculating the LCOE and LCOH include a 20-year time horizon, a discount rate of 7%, and a degradation rate of 0,2% per year for the CSP plant and 0.6% per year for the PV plant

3. Results and discussion

The CSP plant was validated using data from the Gema Solar plant [33] located in Seville, Spain, while the PV plant was validated with data from the Adrar Solar plant [34] located in Adrar, Algeria. Finally, the electrolyzer was validated with data from Ioroi et al. [35].

Table 5 presents the results of the annual electricity production (E), the capacity factor (cf) of the power plants, the annual hydrogen production (H), the annual water consumption of the electrolyzer (H_2O), and the levelized costs of electricity and hydrogen for 2024 and 2030. Case 4 produces the largest amount of hydrogen due to its higher electricity production and larger electrolyzer capacity; however, it does not result in the lowest levelized costs. Results yield a minimum LCOH of 5,76 USD/kg H_2 and a maximum of 6,60 USD/kg H_2 for the current scenario, while for the future scenario, values range between 2,86 and 4,26 USD/kg H_2. The minimum LCOE and LCOH in both scenarios are achieved in Case 1. Therefore, Case 1 is the most recommended, despite having a lower capacity factor and lower hydrogen production

Tab. 5: Results of electricity, hydrogen, LCOE and LCOH

Case	E kWh/year	cf %	H kg H_2/year	H_2O kg H_2O/year	LCOE USD/MWh		LCOH USD/kg H_2	
					2024	2030	2024	2030
Case 1	54.825.847	31,3	974.886	8,773,974.1	37,30	15,74	5,76	2,86
Case 2	150.207.389	86,2	2.610.582	23,495,240.1	85,15	57,04	6,60	4,26
Case 3	186.616.790	53,4	2.665.916	23,993,244.9	79,14	50,18	6,37	3,94
Case 4	205.033.237	58,7	3.640.271	32,762,440.8	72.36	45.99	6,37	3,88

The LCOH values for both 2024 and 2030 are not competitive compared to the costs of hydrogen produced from fossil fuels (grey hydrogen), which range from 1,2 to 2,3 USD/kg H_2 [2], [36]. According to the IEA, the current LCOH for green hydrogen ranges between 3 and 7,5 USD/kg H_2 [1], while IRENA estimates it to be between 4 and 5 USD/kg H_2 for a PV system in Chile [37]. By 2030, there will be a significant reduction in costs; however, they do not fall below 2 USD/kg H_2

Figure 2 presents the breakdown of the LCOH for all cases. In Case 1, which has the lowest LCOH, the distribution in the 2024 scenario is 51,1%, 36,4%, 12,0%, and 0,5% for CAPEX, energy consumption, O&M, and water consumption, respectively. For the 2030 scenario, the distribution is 52,6%, 30,9%, 15,4%, and 1,1%, respectively

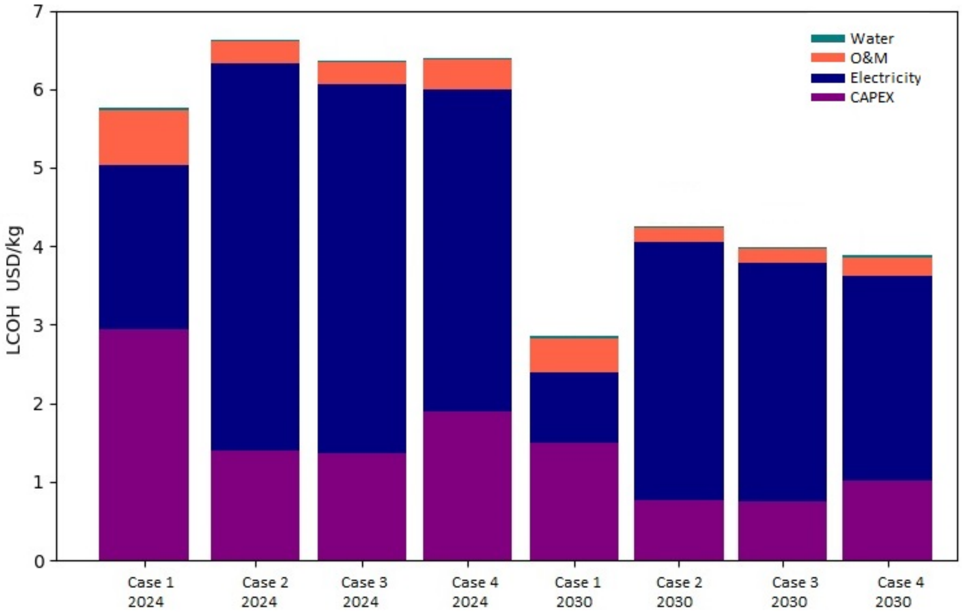
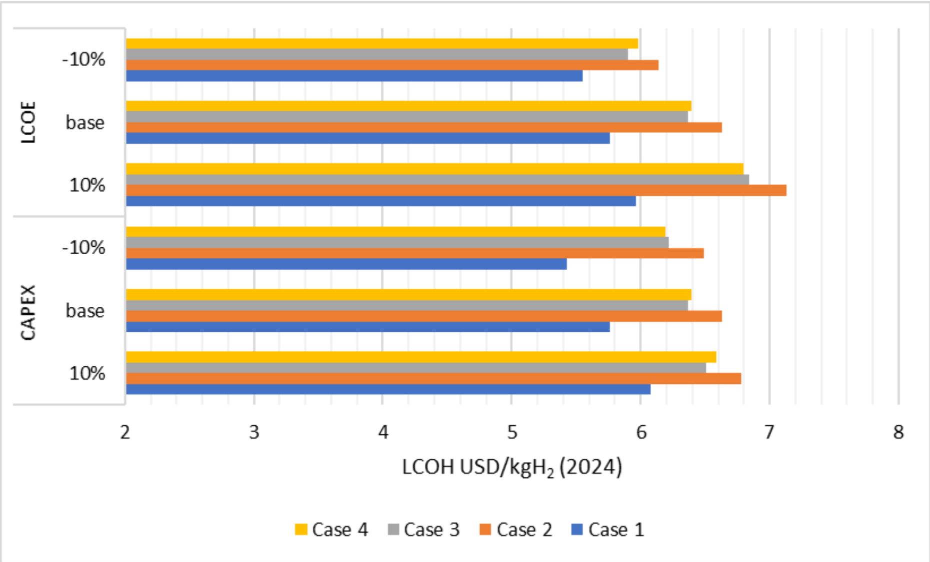
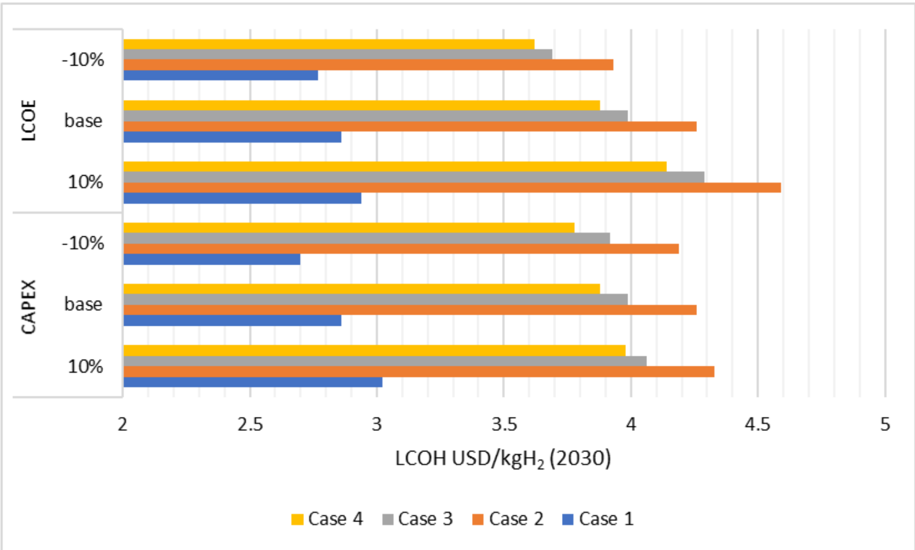


Fig. 2: Breakdown of the levelized cost of hydrogen.

A sensitivity analysis is conducted to quantify the impact of varying key parameters on the LCOH. The selected parameters are the LCOE and CAPEX of the PEM electrolyzer, both of which were varied within a range of ±10% of their base values, to proceed with the new calculation of the LCOH. The results are shown in Figure 3. From an economic standpoint, it has been identified that none of the solar hydrogen production pathways achieve costs below 2 USD/kgH_2 in the current scenario (2024). Therefore, it can be concluded that it is currently challenging for green hydrogen to compete economically with fossil fuel-based hydrogen production. While this situation would persist into 2030, the sensitivity analysis reveals that simply reducing the cost of energy and/or the cost of investment would allow achieving grey hydrogen levels.



(a)



(b)

Fig. 3: Sensitivity analysis a) Current scenario (2024), b) Future scenario (2030)

4. Conclusions

The technical and economic feasibility of hydrogen production from solar energy was assessed, integrating a CSP plant, PV, and PEM electrolyzer operating in off-grid mode. Four cases were evaluated considering three configurations: Case 1 involves PV-PEM, Case 2 CSP-PEM, Case 3 is a hybrid CSP-PV-PEM, and the final case is similar to Case 3 but with a larger PEM plant.

The production of green hydrogen in all evaluated cases exceeds 2 USD/kg H_2, both for the current (2024) and future (2030) scenarios. Therefore, under these conditions, green hydrogen is not economically competitive with grey hydrogen. However, as electricity prices and electrolyzer investment costs decrease and efficiency improves, green hydrogen could become competitive.

The configuration that achieves the minimum LCOH is Case 1, which integrates a PV plant with an electrolyzer. Increasing the capacity factor of the PV plant, without increasing investment costs, could further reduce the LCOH; the same would apply to the CSP plant.

A hybrid solar plant offers complementary or additional benefits, such as greater stability and reliability in hydrogen production, as it is more flexible and less dependent on daily and seasonal variations in solar resources. However, the high investment costs of this technology result in a higher LCOH compared to a PV-PEM plant but lower than a CSP-PEM plant.

The residual heat from the CSP and PV plants could be utilized for cogeneration, using this heat to preheat the water for the PEM plant, thereby increasing system efficiency and potentially reducing the LCOH.

Future work will evaluate the performance of the plants in cogeneration mode and analyze the transient operation of the electrolyzer in more detail

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