SolarPACES 2024, 30th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

CSP Integration, Markets, and Policy

https://doi.org/10.52825/solarpaces.v3i.2437

Published: 19 Nov. 2025

Hydrogen Production Through Renewable Energies in Areas of High Irradiation Conditions

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Abstract. This study evaluates the operation of a Proton Exchange Membrane (PEM) electrolyzer and an Alkaline Water Electrolyzer (AWE), coupled with Concentrated Solar Power (CSP), Photovoltaic (PV), and Wind Turbine (WT) power plants in a region characterized by high solar irradiance and moderate wind speeds. Each technology is modeled and integrated into fourteen different configurations, seven of which are coupled with a PEM electrolyzer, and the remaining seven with an AWE electrolyzer. Hourly simulations are conducted for one year to determine annual hourly production. Subsequently, the Levelized Cost of Electricity (LCOE) and the Levelized Cost of Hydrogen (LCOH) are calculated for two scenarios: the current state and projections for 2030. Results indicate that the LCOE ranges from 48.19 to 118.18 USD/MWh, while the LCOH varies from 3.56 to 14.13 USD/kg H_2. By 2030, these values are projected to decrease to between 38.57 and 87.99 USD/MWh for LCOE and between 2.87 and 8.22 USD/kg H_2 for LCOH. However, these LCOH values are still higher than those for grey hydrogen derived from fossil fuels. If reductions in LCOE and electrolyzer investment costs are achieved, green hydrogen could become more cost-competitive. These findings provide critical insights for policymakers considering strategies for green hydrogen production.

Keywords: PEM Electrolyzer, AWE Electrolyzer, CSP, PV, WT

1. Introduction

The supply of electricity and fuels is paramount for contributing to the sustainable development of a country [1]–[3]. Energy availability is a strategic priority in today's society. Green hydrogen could replace fossil fuels as it becomes more competitive, thereby contributing to the decarbonization of the energy matrix [3]. The most relevant technologies for hydrogen production include Proton Exchange Membrane Electrolyzers (PEM), Alkaline Water Electrolyzers (AWE), and Solid Oxide Electrolyzer Cells (SOEC) [4]. Electrolyzers require electricity and high-purity deionized water to operate. If the electricity used is renewable, the hydrogen produced is termed green hydrogen. Renewable electricity can be generated through Concentrated Solar Power (CSP), Photovoltaic (PV), and Wind Turbine (WT) plants, among others, where the availability of solar and wind resources is crucial. Renewable energies have the advantage of emitting no greenhouse gases, contributing to the decarbonization of the energy matrix, while also generating local employment and enhancing national energy independence [5], [6].

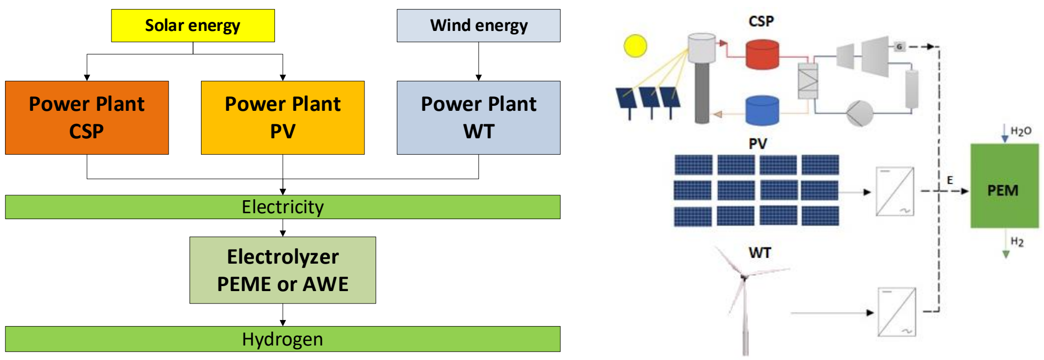
Chile has a high potential for renewable energy, with 152 GW of CSP (Concentrated Solar Power), 2086 GW of PV (Photovoltaic), and 81 GW of wind energy capacity [7]. Globally, it is projected that the Levelized Cost of Hydrogen (LCOH) from hybrid solar photovoltaic and on-shore wind systems could reach as low as 1.5 USD/kgH2 [6]. Regarding the integration of the relevant technologies, Ceylan and Devrim [8] evaluated the integration of PV, WT (Wind Turbine), and FC (Fuel Cell) power plants with a PEM electrolyzer. The designed system was examined both on-grid and off-grid, yielding LCOE values of 0.223 USD/kWh and 0.416 USD/kWh, respectively. Lykas et al. [9] and Sacit et al. [10] present a review of multigeneration systems powered by solar and wind energy, comparing hydrogen production systems. Al-Shetwi et al. [11] conducted a techno-economic analysis of five different hybrid renewable energy systems, showing that the grid-connected PV-WT system is the most advantageous, with an LCOE of 48.0 USD/MWh. Moraga et al. [12] evaluated the integration of CSP, PV, PEM, and AWE systems, where the PW-AWE configuration had the lowest LCOE and LCOH. Leiva-Illanes et al. [13] conducted a techno-economic analysis on the integration of PEM electrolyzers with solar power plants, including both CSP and PV systems, in northern Chile. Their findings indicate that the LCOH ranges from a minimum of 5.76 USD/kg H_2 to a maximum of 6.63 USD/kg H_2. In contrast, projections for 2030 suggest a significant cost reduction, with LCOH values expected to range between 2.86 and 4.26 USD/kg H_2.

This study evaluates the integration of PEM and AWE electrolyzers with renewable energy power plants (CSP, PV, and WT) to identify the optimal configurations for producing both products simultaneously in a location with high solar irradiance.

2. Methodology

Hydrogen and electricity production from solar and wind energy is evaluated. The plant sizes and locations for operation are determined, and they are modeled using specialized software to obtain the annual hourly production of each product. Subsequently, the levelized costs of each product are calculated, and the main variables are subjected to sensitivity analysis.

A central tower CSP plant with Thermal Energy Storage (TES), a PV solar field, and a WT park are modeled. The electricity generated is used to produce hydrogen directly with either a PEM electrolyzer or an AWE electrolyzer. Surplus electricity is fed into the electrical grid. Figure 1 presents the general schematic of the evaluated systems and one of the analyzed cases. A total of fourteen cases are evaluated, as follows: 1) CSP-PEM, 2) CSP-AWE, 3) PV-PEM, 4) PV-AWE, 5) WT-PEM, 6) WT-AWE, 7) CSP-PV-PEM, 8) CSP-PV-AWE, 9) CSP-WT-PEM, 10) CSP-WT-AWE, 11) PV-WT-PEM, 12) PV-WT-AWE, 13) CSP-PV-WT-PEM, and 14) CSP-PV-WT-AWE.



(a) (b)

Figure 1. *System configuration. a) General diagram b) CSP-PV-WT-PEM case*

The CSP and PV plants are modeled using SAM software [14], [15], while the WT plant is modeled using the Wind Explorer [16]. The selected site for evaluation is located in northern Chile (southern hemisphere), near the Cerro Dominador Solar Power Plant, at latitude - 22.77191, longitude -69.47994, and an altitude of 1512 meters above sea level. This location has high levels of solar irradiation: 10.62 kWh/(m² day) of direct normal irradiation, 7.28

kWh/(m² day) of global horizontal irradiation, an average wind speed of 5.2 m/s, and a cloud frequency of 3% [16], [17]. Table 1 presents the key parameters for the CSP, PV, and WT plants used to configure the evaluated systems.

Table 1. *Main characteristics of the evaluated power plan [14]–[17].*

Parameter	**Unit**	**Value**
CSP (Tower type)		
Power	MW	100
Design point	W/m^2	1010
Solar multiple	-	2.684
Thermal cycle efficiency	-	0.445
Solar tower thermal fluid	°C	565/290
TES hours	h	15
TES types		2 tanks
Number of heliostats	-	9508
Heliostat area (each)	m^2	115.702
PV plant		
Power	MW_{dc}	100
Tracking and orientation	-	fixed
PV module	-	SunPower SPR-E19-310
Nominal efficiency	%	19.02
Maximum power (Pmp)	W_{dc}	310.149
Inverter	-	Sungrow Power Supply SC2500U
Efficiency	%	97.532
Maximum AC power	W_{ac}	2 507 195.0
Maximum DC power	W_{dc}	2 557 916.0
WT plant		
Power	MW	100.5
Wind turbine model	-	Acciona AW 77
Loss factor	-	0.17
Nominal power (each	kW	1500
Rotor diameter	m	77

Electricity production is calculated hourly over an annual horizon. The capacity factor (cf) is determined using Equation 1, where E_{annual} is the annual electricity production and $E_{nominal}$ is the nominal annual electricity production, calculated using Equation 2.

$$cf = \frac{E_{annual}}{E_{nominal}} \tag{1}$$

$$E_{nominal} = P_{nominal} \cdot 365 \cdot 24 \tag{2}$$

where $P_{nominal}$ is the nominal power of the power plant.

The solar plants (CSP and PV) and wind turbines (WT) generate electricity according to the availability of solar and wind resources, respectively. In the case of the CSP plant, it can generate electricity during periods of low DNI due to cloud cover or even at night, thanks to its TES (Thermal Energy Storage) system, which increases its capacity factor.

In the case of electrolyzers, the curves are modeled according to the methodology outlined by Gallardo et al. [18], considering Equations 3 and 4, where η_{el} is the efficiency of the electrolyzer, LHV_{H_2} is the lower heating value of hydrogen in (kWh/kg), $C_{sp,el}$ is the specific electrical consumption of the electrolyzer in (kWh/kg), $\dot{m}_{H_2}$ is the mass flow rate of hydrogen generated in (kg/h), and P_{el} is the electrical power consumed by the electrolyzer.

$$\eta_{el} = \frac{LHV_{H_2}}{C_{sp,el}} \tag{3}$$

$$\dot{m}_{H_2} = \frac{P_{el}}{C_{sp.el}} \tag{4}$$

The main parameters of the electrolysers evaluated are summarized in Table 2.

***Table 2**. Parameters considered in the modeling of electrolyzers [4], [18].*

Parameter	Unit	PEM	AWE
Nominal P_{el}	MW	100	100
$C_{sp.el}$	kWh/kg	52	49
Mínimum technical	MW	0	10.8
Specific water consumption	L/kg H_2	10	10

To model the dispatch of each case, it is assumed that the electricity generated by the power plants is used for hydrogen production, and that the hydrogen demand is base-load, meaning that the maximum amount of hydrogen will be produced according to the size of the electrolyzer, the availability of electricity, and the technical minimums of each technology. Excess electricity is injected into the grid. The dispatch model was developed using Matlab and Excel, and an hourly dispatch is considered.

Then, with Equations 5, 6 y 7, the LCOE (Levelized Cost of Electricity) is calculated.

$$LCOE = \frac{CAPEX \cdot crf + OPEX}{E_{annual}} \tag{5}$$

$$OPEX = O\&M + C_{fuel} \tag{6}$$

$$crf = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{7}$$

where $CAPEX$ is the investment cost (USD), crf is the capital recovery factor, $OPEX$ is the operatinf expense (USD/año), $O\&M$ is the operation and maintenance cost (USD/year), C_{fuel} is the fuel cost, i is the discount rate, and n is the evaluation horizon (year). A discount rate of 10% and a horizon of 20 years are considered for the evaluation.

Table 3 shows the values considered for performing the LCOE calculation.

***Table 3**. Values to calculate the LCOE [7], [14], [19]*

Parameter	Unit	2024			2030		
		CSP	PV	WT	CSP	PV	WT
CAPEX	USD/kW	3,701	741	1,200	3229	610	850
OPEX	USD/kW/year	66	15	20	50	10	20

Equations 8, 9, and 10 are used to calculate LCOH.

$$LCOH = \frac{CAPEX \cdot crf + OPEX}{m_{H_2}} \tag{8}$$

$$OPEX = O\&M + C_{H_2O} + C_{E\,H_2} \tag{9}$$

$$OPEX = O\&M + m_{H_2} \cdot LCOW + E_{H_2} \cdot LCOE \tag{10}$$

where m_{H_2} is the annual hydrogen production of the electrolyzer (kg/year), C_{H_2O} is the cost of water consumed by the electrolyzer (USD/year), $C_{E\,H_2}$ is the cost of electricity consumed by the electrolyzer (USD/year), y E_{H_2} is the electricity consumed by the electrolyzer (kWh/year).

The data for calculating LCOH are presented in Table 4.

***Table 4**. Main parameters for LCOH calculation [18], [20]*

Parameter	Unit	2024		2030	
		PEM	AWE	PEM	AWE
CAPEX	USD/kW	1,100	650	500	400
O&M	USD/year	2% CAPEX			
Specific water consumption	L/kg H_2	10			

3. Result and discussion

The models for the CSP and PV plants were validated with [14], [15], and the WT plant was validated with [16]. Meanwhile, the electrolyzers were validated with [18].

Table 5 presents the annual production results for electricity and hydrogen, as well as the capacity factors for each case. The CSP plant has the highest capacity factor among the power plants. This is partly due to the fact that this plant includes TES.

***Table 5.** Production of each product.*

Case	PEM				AWE			
	E_{annual}	cf	m_{H_2}	cf H_2	E_{annual}	cf	m_{H_2}	cf H_2
	MWh/year	%	t H_2/year	%	MWh/year	%	t H_2/year	%
CSP	821,869	93.8	15,458	91.8	821,869	93.8	16,402	91.7
PV	211,719	24.2	4,071	24.2	211,719	24.2	4,276	23.9
WT	136,877	15.5	2,632	15.6	136,877	15.5	2,530	14.2
CSP-PV-WT	1,170,465	44.5	15,852	94.1	1,170,465	44.5	16,801	94.0
CSP-PV	1,033,588	59.0	15,733	93.4	1,033,588	59.0	16,683	93.3
CSP-WT	958,746	54.6	15,679	93.1	958,746	54.6	16,619	93.0
PV-WT	348,596	19.8	6,240	37.0	348,596	19.8	6,454	36.1

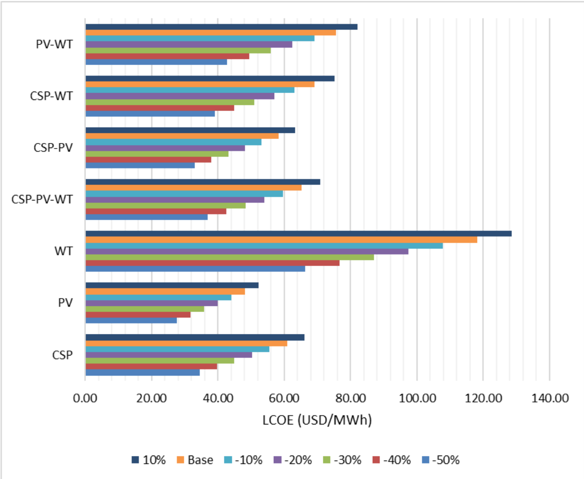
Table 6 shows the results of the levelized costs of LCOE and LCOH.

***Table 6**. Levelized cost results.*

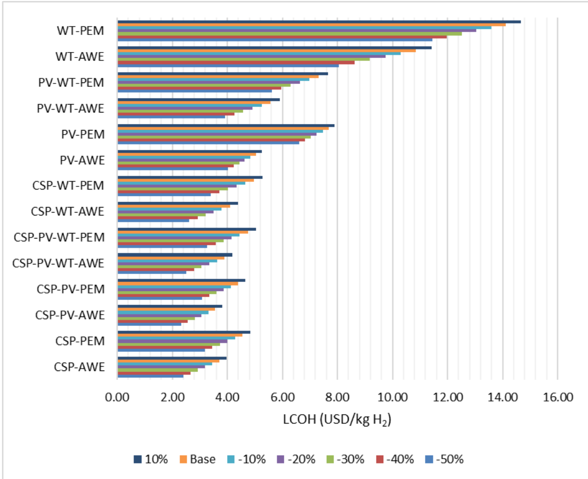
Case	LCOE USD/MWh		LCOH (PEM) USD/kg H_2		LCOH (AWE) USD/kg H_2	
	2024	2030	2024	2030	2024	2030
CSP	60.92	52.23	4.55	3.36	3.70	3.01
PV	48.19	38.57	7.68	4.37	5.04	3.55
WT	118.18	87.99	14.13	8.22	10.86	7.52
CSP-PV-WT	65.32	53.94	4.75	3.44	3.90	3.09
CSP-PV	58.32	49.43	4.39	3.21	3.56	2.87
CSP-WT	69.10	57.34	4.96	3.62	4.10	3.26
PV-WT	75.67	57.97	7.32	4.57	5.57	4.01

It is observed that the LCOH for PEM is higher than for AWE, which is consistent with what is expected and observed in other publications [5], [6], [13], [21]. The justification for these differences is that electrolyzers have varying efficiencies, investment costs, and operation and maintenance costs. On the other hand, the CSP-PV-AWE case has the lowest LCOH, followed by the CSP-AWE case.

A sensitivity analysis was conducted on the capital expenditure (CAPEX) of power generation technologies and electrolyzers for the year 2024, as depicted in Figures 2 and 3, respectively. The results indicate that variations in power plant CAPEX influence both the LCOE and, consequently, the LCOH. In contrast, changes in the CAPEX of electrolyzers affect only the LCOH, without impacting the LCOE.



(a)



(b)

***Figure 2**. Sensitivity analysis on the CAPEX of power plants, effect on the (a) LCOE, (b) LCOH.*

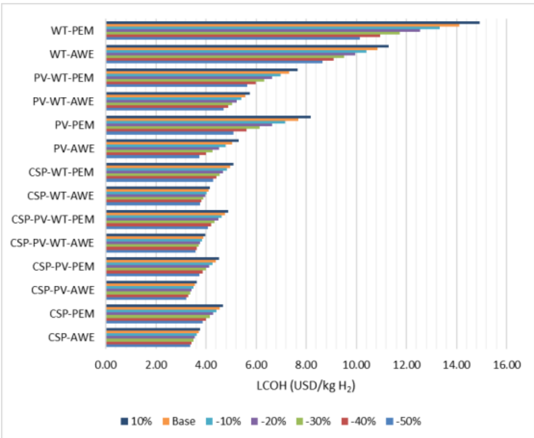


***Figure 3**. Sensitivity analysis on the CAPEX of electrolyzers, effect on LCOH.*

Among the evaluated configurations, PV technology exhibited the lowest LCOE (48.19 USD/MWh), followed by the CSP-PV hybrid system (58.32 USD/MWh). Regarding hydrogen production, the most cost-effective pathways were the CSP-PV-AWE system, achieving an LCOH of 3.56 USD/kg H_2, and the CSP-AWE configuration, with an LCOH of 3.70 USD/kg H_2. These findings highlight the strong dependence of both LCOE and LCOH on CAPEX, underscoring its pivotal role in the economic feasibility of integrated renewable energy systems.

Looking ahead, investment costs for power generation and hydrogen production technologies are expected to decline by 2030, enhancing the competitiveness of both renewable electricity and sustainable hydrogen. This cost reduction is anticipated to accelerate the transition towards a low-carbon energy system by improving affordability and scalability. Additionally, project feasibility assessments must account for key external factors, including solar and wind resource availability, as well as land requirements for large-scale infrastructure deployment, which can significantly influence the overall performance and viability of renewable energy projects.

4. Conclusions

An evaluation of the production of renewable hydrogen and electricity, generated from solar and wind energy using CSP, PV, and WT power plants, and PEM and AWE electrolyzers has been conducted. The main conclusions are as follows:

The potential of solar and wind resources influences the levelized cost of electricity (LCOE), which can render a project unattractive if the potentials are low. The LCOE impacts the levelized cost of hydrogen (LCOH); a lower LCOE results in a lower LCOH. Therefore, one way to enhance the competitiveness of green hydrogen is through lower LCOE. As long as the LCOE of renewable energies is lower than that of fossil fuels, green hydrogen could compete in a free market.

The lowest LCOE is achieved with PV technology (48.19 USD/MWh), followed by CSP-PV (58.32 USD/MWh), CSP (60.92 USD/MWh), and CSP-PV-WT (65.32 USD/MWh). The lowest LCOH is obtained with the CSP-PV-AWE case (3.56 USD/kg H_2), followed by CSP-AWE (3.70 USD/kg H_2) and CSP-PV-WT-AWE (3.90 USD/kg H_2). These values are highly sensitive to the LCOE (or electricity price) and their investment costs.

By 2030, the LCOE ranges from 38.57 USD/MWh to 87.99 USD/MWh, while the LCOH ranges from 2.87 USD/kg H_2 to 8.22 USD/kg H_2. Compared to the price of gray hydrogen at 2 USD/kg H_2, it is clear that green hydrogen is not competitive within a free market. However, incorporating incentives for green hydrogen or imposing taxes on fossil fuels could make green hydrogen more attractive.

Although the AWE electrolyzer has the lowest LCOH, its performance in transient operations affects its ability to operate directly with variable electricity sources, such as those generated by renewable energy systems. Of the two electrolyzers evaluated, the PEM electrolyzer exhibits better performance under these conditions.

Data availability statement

The data supporting this study are available from the corresponding author upon request.

Author contributions

Roberto Leiva-Illanes: Conceptualization, Data curation, Investigation, Methodology, Software, Validation, Writing-original draft, Supervision. Cynthia Herrera: Conceptualization, Writing-review & editing. German Amador: Writing-review & editing, Alvaro Cespedes: Review

Competing interests

The authors have no competing interests that could have influenced the work presented.

Funding

This research work was funded by the PID2301-UTFSM project and the GIEAS (Energy, Water, and Sustainability Research Group) of the UTFSM.

Acknowledgement

Thanks to the PID2301-UTFSM project and the GIEAS of the UTFSM.

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