Feasibility of Green Hydrogen Storage in Chile: Influence of Electrolysis Type, Solar Irradiance, and Storage Technology

Roberto Leiva-Illanes[1,2] and Cynthia Herrera[1]

[1] Grupo de Investigación en Energía, Agua y Sostenibilidad/Universidad Técnica Federico Santa María, Viña del Mar (Chile)

[2] Grupo de Investigación en Movilidad y Combustibles Alternativos/Universidad Técnica Federico Santa María, Valparaíso (Chile)

*Correspondence: roberto.leiva@usm.cl

Abstract

The technical and economic feasibility of green hydrogen production and storage in Chile is examined, considering the country's geographical characteristics and local energy resources. The methodology involves modeling electrolysis systems based on Proton Exchange Membrane (PEME) and Alkaline Water Electrolysis (AWE) technologies, powered by photovoltaic (PV) solar plants located in three representative regions of the country, each with different levels of solar irradiance. Two hydrogen storage options are evaluated, compressed gaseous hydrogen and liquid hydrogen, and system operation is analyzed both with and without curtailment. The results reveal that both the Levelized Cost of Energy (LCOE) and the Levelized Cost of Hydrogen (LCOH) increase as solar irradiance decreases. For instance, with a Global Horizontal Irradiance (GHI) of 2329 kWh/m²/year, the LCOE reached 53.89 USD/MWh, while the LCOH was 8.63 and 5.63 USD/kg H_2 for PEME and AWE electrolyzers, respectively. In contrast, for a GHI of 1865 kWh/m²/year, the corresponding values were 68.80 USD/MWh and 11.02 and 7.20 USD/kg H_2. Moreover, the Levelized Cost of Storage (LCOS) was 0.84 USD/kg H_2 for compressed hydrogen (CGH_2) and 2.65 USD/kg H_2 for liquid hydrogen (LH_2) in the region with the highest solar irradiance, increasing to 1.07 and 3.38 USD/kg H_2, respectively, in the region with the lowest irradiance. These findings highlight the comparative advantages of compressed hydrogen storage, while also identifying specific scenarios in which liquid hydrogen could become a viable alternative despite its higher technical and energy requirements.

Keywords: PV, Hydrogen, LCOS, LCOH, PEM, AWE, Curtailment

1. Introduction

The growing concern over the effects of climate change and the progressive depletion of fossil fuels have driven a global transition toward renewable energy sources. In pursuit of carbon neutrality, numerous countries have implemented policies aimed at reducing CO_2 emissions through the large-scale integration of clean energy into their power matrices (IEA, 2019; Ma *et al.*, 2024). In Latin America, Chile has positioned itself as a regional leader due to its extraordinary solar potential in the northern region, where Global Horizontal Irradiance (GHI) levels rank among the highest in the world (Ministry of Energy of Chile, 2020). However, the inherent intermittency of photovoltaic generation poses significant challenges for power system stability and the management of surplus energy (Ceylan and Devrim, 2023). In this context, the development of energy storage systems has emerged as a key strategy to ensure supply flexibility and security.

Among the various alternatives, green hydrogen stands out as a promising energy carrier, capable of storing large amounts of energy over long periods and facilitating the integration of renewable energy across different economic sectors, including transportation, industry, and energy exportation. Nevertheless, the very low density of hydrogen in its gaseous state (GH_2) presents a major technical and economic challenge for large-scale storage, transport, and commercialization. To overcome these limitations, technologies have been developed to increase its energy density through compression (CGH_2), liquefaction (LH_2), or cryo-compression (CcH_2) (Gallardo *et al.*, 2021; Basnet *et al.*, 2023). Compressed gaseous hydrogen storage (CGH_2) currently

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represents the most mature and commercially widespread option. This system typically operates within pressure ranges between 200 and 700 bar, depending on the application, and requires less energy than liquefaction. Furthermore, compression technology and tank materials have achieved high levels of reliability, enabling their use in both stationary and mobile applications. However, the cost of compression systems, equipment maintenance, and limited volumetric density remain critical factors that constrain its competitiveness compared to other storage options (Martínez de León *et al.*, 2024; Moran *et al.*, 2024). Conversely, cryogenic storage of liquid hydrogen offers a significantly higher density, facilitating long-distance transport; nevertheless, it presents important technical barriers, such as the high energy demand of the liquefaction process (~13.8 kWh/kg H_2) and evaporation losses during storage (1–5% per day) (Zhang *et al.*, 2023).

Regarding production, water electrolysis is the most mature technology for generating green hydrogen using electricity from renewable sources. The main types of electrolyzers include: alkaline electrolyzers (AWE), recognized for their low cost and high durability; proton exchange membrane electrolyzers (PEME), valued for their dynamic operation and higher current density; and solid oxide electrolyzers (SOEC), which offer higher efficiencies at elevated temperatures, although they remain less commercially developed (Abdelsalam *et al.*, 2024; Kourougianni *et al.*, 2024). Furthermore, projections of the levelized cost of green hydrogen indicate that it could range between 1 and 3 USD/kg H_2 in low solar cost scenarios, with a potential reduction to around 1 USD/kg H_2 by 2050, reinforcing hydrogen's potential as a central component of the energy transition ("Global Hydrogen Review 2021," 2021).

The direct coupling of photovoltaic (PV) solar plants with electrolysis systems constitutes a key strategy to maximize the utilization of renewable generation and reduce losses associated with energy curtailment. Curtailment occurs when electricity production exceeds demand or grid capacity, requiring the limitation of solar energy injection. In PV–electrolyzer hybrid systems, surplus electricity can be used to produce green hydrogen, converting otherwise unused electrical energy into a high-value energy carrier. However, the intermittent and variable nature of solar irradiance introduces significant operational challenges, particularly for alkaline electrolyzers (AWE), which exhibit lower dynamic flexibility in response to power fluctuations. In contrast, proton exchange membrane electrolyzers (PEME) provide faster transient response, making them more suitable for operation under variable generation conditions. Optimizing the coupling between the size of the solar field and the electrolyzer capacity, expressed as the PV-to-electrolyzer power ratio, is crucial to balance system efficiency, minimize curtailment, and reduce the levelized cost of hydrogen (LCOH) (Martínez de León *et al.*, 2024; Fang *et al.*, 2025).

Recent studies (de Oliveira Junior, 2013; Abdin, Khalilpour and Catchpole, 2022; Ibáñez-rioja *et al.*, 2023; Olabi *et al.*, 2023; Kourougianni *et al.*, 2024; Leiva-Illanes *et al.*, 2024, 2025; Ma *et al.*, 2024) highlight that the techno-economic viability of green hydrogen critically depends on the combination of electrolyzer type, available solar irradiance, and storage technology. Within this framework, the present study evaluates the technical and economic feasibility of green hydrogen storage in Chile, considering different electrolyzer types, storage alternatives, and solar irradiance levels. The goal is to identify the most efficient and sustainable configurations for solar hydrogen production and storage in the Chilean energy context, providing quantitative evidence to support the development of a competitive and sustainable hydrogen economy.

2. Methodology

The production of green hydrogen in Chile is evaluated through photovoltaic (PV) systems coupled with electrolyzers (EL) and hydrogen storage systems in regions with different levels of solar irradiance. The generated hydrogen is stored either as compressed gaseous hydrogen (CGH_2) or as liquid hydrogen (LH_2), each with thermodynamic and operational characteristics that directly influence technical performance, investment costs, and overall system feasibility. Plant sizing is carried out based on a characteristic hydrogen demand, seeking to balance the installed solar generation capacity, electrolyzer power, and storage capacity. The systems were modeled using the System Advisor Model (SAM) (National Renewable Energy Laboratory (NREL), 2024), MATLAB (MathWorks, 2025), and irradiance datasets from the Chilean Solar Explorer (Ministry of Energy of Chile, 2025). Each model was validated through comparison with technical and operational data from reference facilities currently in operation and/or reported in the literature. The constitutive equations of the models allow the estimation of photovoltaic electricity production, hourly hydrogen generation, and key economic indicators: Levelized Cost of Electricity (LCOE), Levelized Cost of Hydrogen (LCOH), and Levelized Cost of Storage (LCOS). These indicators enable consistent comparison of different technological configurations and irradiance conditions, providing a quantitative basis for assessing the techno-economic feasibility of green hydrogen within the Chilean energy context.

Figure 1 illustrates the overall scheme of the evaluated configurations. Two systems are analyzed: one integrating a photovoltaic (PV) plant with a proton exchange membrane electrolyzer (PEME) and another with an alkaline electrolyzer (AWE). Both systems (PV-PEME and PV-AWE) are subsequently evaluated coupled with hydrogen storage systems, including compressed gaseous hydrogen (CGH_2) and liquid hydrogen (LH_2).

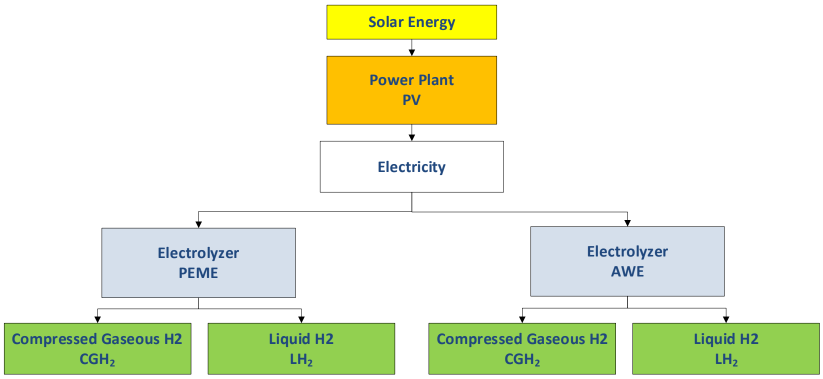


Figure 1: Overall scheme.

Three regions of Chile were evaluated: northern zone (L1), Huasco, at latitude -28.54, longitude -70.593, 1302 m above sea level, with a Global Horizontal Irradiance (GHI) of 2329 kWh/m²/year; central zone (L2), Valle Aconcagua, at latitude -33.8333, longitude -70.6, 830 m above sea level, with a GHI of 2113 kWh/m²/year; and southern zone (L3), Valle del Ñuble, at latitude -35.6, longitude -71.95, 153 m above sea level, with a GHI of 1865 kWh/m²/year (Ministry of Energy of Chile, 2025).

In the modeling, a 100 MW installed PV solar plant was selected, using SunPower SPR-E19-310-COM photovoltaic panels with a nominal efficiency of 19.02%, maximum power $P_{mp,ref}$ of 310.149 (W), maximum power voltge $V_{mp,ref}$ of 54.7 (V), maximum power current $I_{mp,ref}$ of 5.7 (A), open circuit voltage $V_{oc,ref}$ of 64.4 (V), and short circuit current $I_{sc,ref}$ of 6.0 (A) (Gilman, 2015; Herrera, Leiva-Illanes and Amador, 2024).

The electrical output power is calculated by Equation 1.

$$P_{DC} = \sum_{n=1}^{Nsub} N_m \cdot N_{s,n} \cdot P_{mp,n} \cdot F_{dcss,n} \quad (1)$$

where P_{DC} is the total direct current (DC) power generated by the photovoltaic array (W), $Nsub$ is the total number of photovoltaic subarrays considered in the system, Nm is the number of photovoltaic modules connected in parallel within each subarray, $N_{s,n}$ is the number of modules connected in series in subarray n, $P_{mp,n}$ is the maximum power point (MPP) of a photovoltaic module in subarray n (W), $F_{dcss,n}$ represents losses due to self-shading, mismatch, snow, and other factors.

Under operating conditions, the current and voltage are calculated by Equation 2.

$$I = I_L - I_0 \cdot \left(e^{\frac{V+I\cdot R_s}{n\cdot V_t}} - 1\right) - \frac{V + I \cdot R_s}{R_{sh}} \quad (2)$$

where I is the output current of the photovoltaic module (A), V is the output voltage of the photovoltaic module (V), I_L is the generated current (A), I_0 is the diode saturation current, R_s is the series resistance of the module, R_{sh} is the shunt resistance of the module, n is the diode ideality factor, and V_t is the thermal voltage.

The current is adjusted to the actual operating conditions by Equation 3, and the alternating current (AC) power is calculated by Equation 4.

$$I_L = \frac{G}{G_{ref}} \cdot I_{L,ref} + \alpha \cdot \left(T_C - T_{ref}\right) \quad (3)$$

$$P_{AC} = P_{DC} \cdot \eta_{inv} \tag{4}$$

where G is the solar irradiance incident on the plane of the module (W/m²), G_{ref} is the reference solar irradiance under standard test conditions (STC), $I_{L,ref}$ is the short-circuit current of the module under standard conditions, α is the temperature coefficient of the short-circuit current (A/°C), T_C is the photovoltaic cell temperature (°C), T_{ref} is the reference temperature under standard conditions (25 °C), P_{AC} is the electrical power in alternating current delivered by the inverter (W), P_{DC} is the electrical power in direct current generated by the photovoltaic field (W), and η_{inv} is the inverter efficiency (dimensionless), representing losses in the DC/AC conversion.

The electrolyzers are modeled according to Equations 5, 6, and 7 (Leiva-Illanes *et al.*, 2024),

$$V_{H_2} = \eta_F \cdot \frac{n_c \cdot R \cdot I_{EL} \cdot T_{amb} \cdot 3600}{F \cdot P \cdot z} \tag{5}$$

$$\dot{n}_{H_2} = \eta_F \cdot \frac{n_c \cdot I_{EL}}{z \cdot F} \tag{6}$$

$$\dot{m}_{H_2} = \frac{P_{EL}}{SEC_{EL}} \tag{7}$$

where V_{H_2} is the volume of hydrogen produced (m³/h), η_F is the Faradaic efficiency of the electrolyzer (-), n_c is the number of electrochemical cells in the electrolyzer (-), R is the universal gas constant (J/mol/K), I_{EL} is the input current to the electrolyzer (A), T_{amb} is the ambient temperature (K), F is the Faraday constant (96485 (C/mol), P is the operating pressure of the electrolyzer (Pa), z is the number of electrons transferred during electrolysis (for H_2, z =2), $\dot{n}_{H2}$ is the molar flow rate of hydrogen produced (mol/s), n_c is the number of cells in the electrolyzer (-), $\dot{m}_{H_2}$ is the mass flow rate of hydrogen produced (kg/h o kg/s), P_{EL} is the electrical power consumed by the electrolyzer (W), SEC_{EL} is the specific energy consumption of the electrolyzer (kWh/kg H_2), representing the energy required to produce one unit of hydrogen mass.

PEME and AWE electrolyzers with a nominal power of 100 MWe were modeled, with specific electricity consumption values of 52 and 49 kWh/kg H_2, and technical minimum load levels of 5% and 10%, respectively (Gallardo *et al.*, 2021; Leiva-Illanes *et al.*, 2024). The specific water consumption was assumed to be 10 L/kg H_2. The monthly hydrogen production at each plant is directly influenced by the available solar irradiance in the region where the facility is located.

Compressed gaseous hydrogen is stored at 200 bar, with a compressor-specific energy consumption of 2.5 kWh/kg H_2. For liquid hydrogen, the specific energy consumption is 10 kWh/kg H_2. In both cases, one day of hydrogen storage was considered. The system was configured such that the oversizing ratio $R_{PV/EL}$ (Equation 8) equals 1.

$$R_{PV/EL} = \frac{P_{PV}}{P_{EL}} \tag{8}$$

where $R_{PV/EL}$ is the oversizing ratio, P_{PV} is the nominal installed power of the photovoltaic PV field (MW) and P_{EL} is the nominal power of the electrolyzer (MW).

Regarding the techno-economic indicators, the Levelized Cost of Energy (LCOE), Levelized Cost of Hydrogen (LCOH), and Levelized Cost of Storage (LCOS) are calculated using Equation 9.

$$LCO = \frac{CAPEX + \sum_{i=1}^{N} \frac{OPEX_i}{(1+t)^i}}{\sum_{i=1}^{N} \frac{Production_i}{(1+t)^i}} \tag{9}$$

where $CAPEX$ corresponds to the initial capital investment, $OPEX_i$ represents the operational costs, including operation and maintenance (O&M), energy consumption, inputs, and other expenses, t is the discount rate or weighted average cost of capital (WACC), and, and $Production_i$ is the annual production of the evaluated output. Thus, for the LCOE, it corresponds to the annual energy generated (MWh/year); for the LCOH, to the annual hydrogen production (kg H_2/year); and for the LCOS, to the annual hydrogen stored (kg H_2/year).

In the assessment, a CAPEX of 741, 110, and 650 USD/kWe was considered for the PV plant, PEME, and AWE systems, respectively. An OPEX of 2% of CAPEX, a stack replacement cost of 45% and 30% of CAPEX, and a lifetime of 60,000 h and 80,000 h were assumed for PEME and AWE, respectively. For the storage systems, the CAPEX was 400 and 1200 USD/kg H_2 for CGH_2 and LH_2, respectively (Abdin, Khalilpour and Catchpole, 2022; Gallardo *et al.*, 2022; Kourougianni *et al.*, 2024; Leiva-Illanes *et al.*, 2024). These values include the hydrogen compression equipment and the liquefaction unit, along with the corresponding storage tanks. Finally, a discount rate of 10% and an evaluation period of 20 years were considered.

3. Results and discussion

Figure 2 illustrates the hourly evolution of photovoltaic (PV) electricity generation and hydrogen production using PEME and AWE electrolyzers at two locations with different levels of global solar irradiance, where L1 corresponds to the site with higher irradiance and L3 to the one with lower irradiance. A clearly defined diurnal pattern is observed, with peak solar power generation during midday hours and no production at night, which is directly reflected in the hydrogen output. At site L1, the maximum PV power reaches approximately 90 MW, while at L3 it decreases to around 75 MW, highlighting the effect of higher solar radiation availability at the first location. Similarly, hydrogen production follows the same trend, reaching about 2500 kg H_2/h at L1, exceeding the values observed at L3. The comparison between technologies shows that PEME and AWE electrolyzers yield different outputs under identical conditions; however, the PEME electrolyzer exhibits better performance when operating with variable power from renewable sources. Overall, the figure demonstrates the strong correlation between photovoltaic generation and hydrogen production, emphasizing that the higher solar irradiance at L1 results in a more stable and higher output of both electricity and hydrogen.

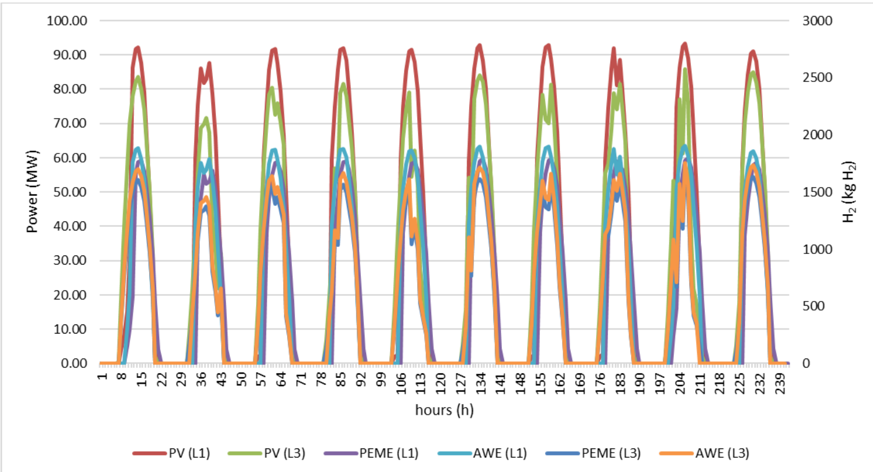


Figure 2: Electricity and Hydrogen Production.

Table 1 shows the annual electricity production (E_{PV}) generated by the photovoltaic (PV) system, considering both the utilization of surplus electricity injected into the grid and the curtailed electricity not consumed by the electrolyzer (E_{PV} curtailment). The table also includes the capacity factor of the PV system without and with curtailment (cf_{PV} and cf_{PVc}, respectively), the electricity effectively consumed by the electrolyzers (E_{EL}), the total hydrogen mass produced (m_{H_2}), and the corresponding capacity factor for each electrolyzer type (cf_{EL})

Table 1: Annual electricity and hydrogen production.

Parameter	L1		L2		L3	
	PEME	AWE	PEME	AWE	PEME	AWE
E_{PV} (kWh/year)	189,344,647	189,344,647	163,360,175	163,360,175	148,300,101	148,300,101
E_{PV} curtailment (kWh/year)	1,691,060	3,195,375	1,087,843	1,086,808	1,416,061	3,651,424
cf_{PV} (%)	21.6	21.6	18.6	18.6	16.9	16.9
cf_{PVc} (with curtailment) (%)	21.4	21.2	18.52	18.52	16.8	16.5
E_{EL} (kWh/year)	187,653,588	186,149,272	162,272,332	162,273,366	146,884,040	144,648,677
m_{EL} (kg H_2/year)	3,608,723	3,798,965	3,120,622	3,250,552	2,824,693	2,952,014
cf_{EL} (%)	21.4	21.2	18.5	18.2	16.8	16.5

It is observed that, for the same installed capacity, locations with higher solar irradiance (such as L1) achieve greater electricity generation and, consequently, higher annual hydrogen production, resulting in higher capacity factors for both the PV system and the electrolyzers. In contrast, sites with lower irradiance (L3) exhibit reduced generation and energy utilization, leading to lower hydrogen production and less effective use of installed capacity. When comparing electrolyzer technologies, AWE plants produce a higher total amount of hydrogen than PEME systems under the same operating conditions, despite having a slightly lower capacity factor. This difference is attributed to the lower specific energy consumption of the AWE system, meaning it requires less electrical energy per kilogram of H_2 produced. However, PEME systems offer greater operational flexibility and faster dynamic response to the inherent variability of intermittent renewable sources, making them more suitable for direct coupling with photovoltaic generation. Therefore, the results illustrate how solar resource availability and the technological characteristics of electrolyzers directly influence the overall efficiency of the PV–H_2 hybrid system, emphasizing the importance of selecting the optimal technology and location to maximize production and energy utilization.

Table 2 presents the results of the Levelized Cost of Electricity (LCOE) and Levelized Cost of Hydrogen (LCOH) obtained for the three analyzed locations and both electrolyzer technologies (PEME and AWE), considering scenarios with and without curtailment.

Table 2: Levelized Cost of Energy (LCOE) and Hydrogen (LCOH) by Location and Technology

Parameter	Unit	L1		L2		L3	
		PEME	AWE	PEME	AWE	PEME	AWE
LCOE	USD/MWh	53.89	53.89	62.46	62.46	68.80	68.80
$LCOE_c$	USD/MWh	54.38	54.81	62.88	62.88	69.47	70.54
LCOH	USD/kg H_2	8.63	5.63	9.99	6.60	11.02	7.20
$LCOH_c$	USD/kg H_2	8.66	5.67	10.01	6.62	11.05	7.29

In terms of LCOE, it is observed that site L1 exhibits the lowest value (53.9 USD/MWh), positioning it as the most favorable location for photovoltaic plant installation. This lower cost is directly associated with the higher solar irradiance available at L1, which enables greater electricity generation and better utilization of invested capital, thereby reducing the levelized cost of energy. In contrast, sites L2 (62.5 USD/MWh) and L3 (68.8 USD/MWh) present progressively higher costs due to lower solar resource availability, which results in a reduced capacity factor and a relative increase in investment and operational costs per unit of energy generated. When considering the effect of curtailment (LCOEc), a slight increase in costs is observed, on the order of 1%

to 2.5%, reflecting the economic losses associated with excess energy that is neither utilized by the electrolyzer nor injected into the grid. Regarding LCOH, the results show a clear trend depending on both the solar resource and the electrolyzer technology. Across all locations, AWE electrolyzers present a significantly lower hydrogen cost than PEME systems: at L1, 5.63 versus 8.63 USD/kg H_2; at L2, 6.60 versus 9.99 USD/kg H_2; and at L3, 7.20 versus 11.02 USD/kg H_2. This difference, consistent with literature reports, is primarily explained by the lower capital cost and lower specific energy consumption of alkaline technology, which compensates for its lower dynamic efficiency under power fluctuations from renewable sources. Furthermore, the increase in LCOH at sites with lower irradiance (L2 and L3) reflects the combined effect of a higher LCOE and reduced hydrogen production, raising the unit production cost. The effect of curtailment on LCOH (LCOHc) is marginal but positive, increasing values by approximately 0.03 USD/kg H_2. This increase demonstrates that even small amounts of unused energy impact on the total hydrogen cost by reducing the fraction of electricity effectively utilized by the electrolyzers. In summary, the results confirm that solar resource availability is the most decisive factor in the levelized costs of both energy and hydrogen, while the selection of electrolyzer technology defines the economic competitiveness of the system. AWE-based plants exhibit lower hydrogen production costs under stable operation scenarios, whereas PEME systems offer operational advantages under intermittent regimes, albeit with higher investment and production costs.

Figure 3 shows the variation of the Levelized Cost of Electricity (LCOE) as a function of the ratio between the installed photovoltaic field power (P_{PV}) and the nominal electrolyzer power (P_{EL}), analyzing scenarios without curtailment and with curtailment. It is observed that, as the oversizing ratio (P_{PV}/P_{EL}) (Equation 8) increases, the LCOE initially tends to decrease due to better utilization of the solar resource and higher total electricity and hydrogen production. However, when the photovoltaic field size exceeds a certain threshold relative to the electrolyzer capacity, excess energy is generated that cannot be fully used for hydrogen production, resulting in losses due to curtailment. In this regime, the corrected LCOE (with curtailment) progressively increases, as part of the PV investment does not contribute effectively to the system's useful output. Consequently, the figure highlights the existence of an optimal (P_{PV}/P_{EL}) ratio, in which the system achieves a balance between solar radiation utilization and the electrolyzer's conversion capacity, minimizing the total LCOE. Ratios below this optimum result in underutilization of the solar potential (lower generation), while excessive ratios lead to photovoltaic overcapacity and increased energy losses. These results emphasize the importance of an integrated PV–electrolyzer system sizing, where proper adjustment of the oversizing ratio maximizes the system's economic efficiency and reduces the impact of curtailment on the levelized cost of electricity.

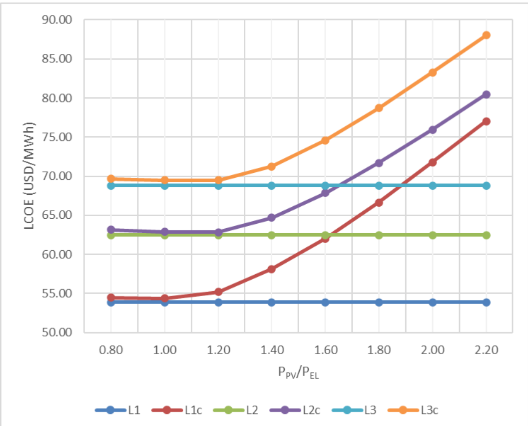
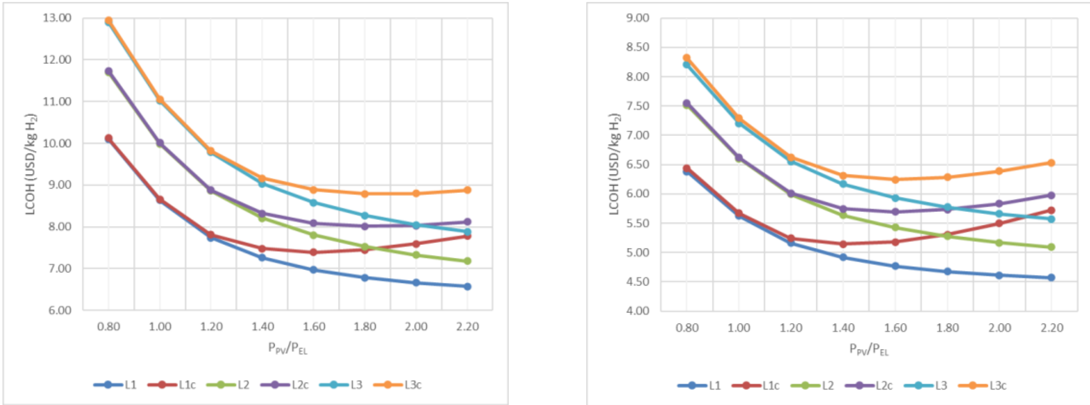


Figure 3: Effect of variations in the oversizing ratio (P_{PV}/P_{EL}) on the LCOE.

Figure 4 illustrates how electrolyzer performance varies as a function of the ratio between the photovoltaic field capacity (P_{PV}) and the electrolyzer capacity (P_{EL}), considering two scenarios: without curtailment (all excess energy utilized) and with curtailment (part of the excess energy limited or unused). For PEME electrolyzers (Figure 4a), low P_{PV}/P_{EL} ratios imply that the electrolyzer does not reach its nominal capacity, limiting hydrogen production. As the ratio increases, the electrolyzer approaches its maximum capacity, but excessively high ratios generate curtailment under the constrained injection scenario, reducing the efficiency of available solar energy utilization. For AWE electrolyzers (Figure 4b), a similar trend is observed; however, they exhibit higher tolerance to energy variations, and the difference between scenarios with and without curtailment is less pronounced, indicating that they can handle excess energy with minimal losses. In general, without curtailment, all available energy is utilized, increasing the electrolyzer capacity factor, whereas with curtailment, part of the energy is wasted, slightly reducing hydrogen production but avoiding oversizing and unnecessary costs. These results highlight that selecting the appropriate P_{PV}/P_{EL} ratio is critical to optimize hydrogen production and the economic efficiency of the system, and that the operational flexibility of the electrolyzer type influences how effectively the available solar energy is used.



a) b)

Figure 4: Effect of variations in the oversizing ratio (PPV/PEL) on the LCOH. a) PEME. b) AWE

Table 3 presents the Levelized Cost of Storage (LCOS) values for each analyzed plant, comparing compressed gaseous hydrogen (CGH_2) storage and liquid hydrogen (LH_2) storage via liquefaction, considering both PEME and AWE electrolyzers. The results show that the LCOS for liquid hydrogen is significantly higher than that for gaseous hydrogen across all configurations, reflecting the greater technical and energetic complexity of liquefaction, which requires operation at extremely low temperatures using specialized equipment such as cryogenic systems, as well as high energy consumption during the liquefaction process. For compressed gaseous hydrogen, LCOS values remain relatively low and stable across plants and technologies, with minimal differences between PEME and AWE, indicating that the electrolyzer type has a limited impact on gaseous storage costs. In contrast, for LH_2, LCOS progressively increases from L1 to L3, reflecting the effects on the required infrastructure and operational costs. When comparing PEME and AWE, differences are small in all cases, although slightly higher for AWE in larger-scale scenarios due to variations in production profiles and electrolyzer efficiency.

Table 3: Levelized Cost of Hydrogen Storage (LCOS)

Parameter	Unit	L1		L2		L3	
		PEME	AWE	PEME	AWE	PEME	AWE
LCOS CGH_2	USD/kg H_2	0.84	0.84	0.97	0.98	1.07	1.08
$LCOS_c$ CGH_2	USD/kg H_2	0.84	0.85	0.97	0.99	1.07	1.09
LCOS LH_2	USD/kg H_2	2.65	2.67	3.06	3.11	3.38	3.42
$LCOS_c$ LH_2	USD/kg H_2	2.65	2.67	3.07	3.11	3.39	3.44

4. Conclusion

The techno-economic feasibility of green hydrogen production and storage in Chile was evaluated, considering the country's geographic diversity and solar potential. Through the modeling of photovoltaic (PV) systems coupled with PEME and AWE electrolyzers, scenarios with different levels of solar irradiance and operational conditions were analyzed, including curtailment management and two storage alternatives: compressed gaseous hydrogen (CGH_2) and liquid hydrogen (LH_2). The main conclusions are summarized as follows:

The results show that solar resource availability is the primary factor determining hydrogen production and the economic efficiency of PV–H_2 hybrid systems. Locations with higher irradiance can reach up to 96.1 MW of installed PV capacity and produce approximately 3.8×10^6 kg H_2/year with alkaline electrolyzers, whereas regions with lower irradiance experience significantly reduced production, highlighting the importance of selecting sites with high solar radiation.

Regarding electrolyzer technologies, PEME systems stand out for their operational flexibility and fast response to solar power variability, while AWE systems exhibit lower specific energy consumption, generating higher annual hydrogen output despite slightly lower capacity factors. Levelized costs of electricity and hydrogen reflect this trend: the lowest LCOH values are achieved with AWE, reaching 5.6 USD/kg H_2 under high-irradiance conditions, whereas PEME systems show higher LCOH, up to 11 USD/kg H_2 in lower-irradiance scenarios.

The sizing of the PV-to-electrolyzer power ratio is critical for maximizing economic efficiency: ratios that are too low result in underutilization of solar energy, while excessively high ratios lead to curtailment losses and increased energy and hydrogen costs.

In terms of storage, compressed gaseous hydrogen is more economical and flexible, with LCOS ranging from 0.84 to 1.09 USD/kg H_2, whereas liquid hydrogen storage via liquefaction increases costs up to 3.44 USD/kg H_2 due to cryogenic infrastructure requirements and additional energy consumption.

Overall, the optimization of a PV–H_2 system depends on the simultaneous integration of site selection, electrolyzer technology, relative PV-to-electrolyzer sizing, and storage strategy to maximize hydrogen production, minimize levelized costs, and ensure economic and operational feasibility.

As future work, the flexibility and efficiency of PV–H_2 hybrid systems will be evaluated through the integration of additional renewable sources and the development of dynamic dispatch strategies to optimize electrolyzer operation in response to hourly variations in solar resource and hydrogen demand.

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6. References

Abdelsalam, R.A. *et al.* (2024) “Green hydrogen production plants: A techno-economic review,” *Energy Conversion and Management*, 319(July), p. 118907. Available at: https://doi.org/10.1016/j.enconman.2024.118907.

Abdin, Z., Khalilpour, K. and Catchpole, K. (2022) “Projecting the levelized cost of large scale hydrogen storage for stationary applications,” *Energy Conversion and Management*, 270(September), p. 116241. Available at: https://doi.org/10.1016/j.enconman.2022.116241.

Basnet, S. *et al.* (2023) “A review on recent standalone and grid integrated hybrid renewable energy systems: System optimization and energy management strategies,” *Renewable Energy Focus* , 46, pp. 103–125. Available at: https://doi.org/10.1016/j.ref.2023.06.001.

Ceylan, C. and Devrim, Y. (2023) “Green hydrogen based off-grid and on-grid hybrid energy systems,” *International Journal of Hydrogen Energy*, 48(99), pp. 39084–39096. Available at: https://doi.org/10.1016/j.ijhydene.2023.02.031.

Fang, L. *et al.* (2025) “Economic analysis of compressed gaseous hydrogen, liquid hydrogen, and cryo-compressed hydrogen storage methods for large-scale storage and transportation,” *International Journal of Hydrogen Energy*, 162(May), p. 150725. Available at: https://doi.org/10.1016/j.ijhydene.2025.150725.

Gallardo, F. *et al.* (2022) “Assessing sizing optimality of OFF-GRID AC-linked solar PV-PEM systems for hydrogen production,” *International Journal of Hydrogen Energy*, 47(64), pp. 27303–27325. Available at: https://doi.org/10.1016/j.ijhydene.2022.06.098.

Gallardo, F.I. *et al.* (2021) “A Techno-Economic Analysis of solar hydrogen production by electrolysis in the north of Chile and the case of exportation from Atacama Desert to Japan,” *International Journal of Hydrogen Energy*, 46(26), pp. 13709–13728. Available at: https://doi.org/10.1016/j.ijhydene.2020.07.050.

Gilman, P. (2015) "SAM Photovoltaic Model Technical Reference," *Solar Energy*, 63(May), pp. 323–333. Available at: https://www.nrel.gov/docs/fy15osti/64102.pdf%0Awww.nrel.gov/publications.

"Global Hydrogen Review 2021" (2021) *Global Hydrogen Review 2021* [Preprint]. Available at: https://doi.org/10.1787/39351842-EN.

Herrera, G., Leiva-Illanes, R. and Amador, G. (2024) *Evaluación tecno-económica para producción conjunta de electricidad e hidrógeno verde con tecnologías hibridas de concentración solar de potencia (CSP) y fotovoltaicas (PV) acopladas a electrolizadores PEM.* Universidad Técnica Federico Santa María.

Ibáñez-rioja, A. *et al.* (2023) "Off-grid solar PV – wind power – battery – water electrolyzer plant : Simultaneous optimization of component capacities and system control," *Applied Energy*, 345(December 2022), p. 121277. Available at: https://doi.org/10.1016/j.apenergy.2023.121277.

IEA (2019) *The Future of Hydrogen. Seizing today's opportunities.* Available at: https://doi.org/10.1787/1e0514c4-en.

Kourougianni, F. *et al.* (2024) "A comprehensive review of green hydrogen energy systems," *Renewable Energy*, 231(May), p. 120911. Available at: https://doi.org/10.1016/j.renene.2024.120911.

Leiva-Illanes, R. *et al.* (2024) "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," in *Proceedings of EuroSun 2024*. Available at: https://proceedings.ises.org/?conference=eurosun2024&doi=10.18086/eurosun.2024.09.04&sort=title&mode=list.

Leiva-Illanes, R. *et al.* (2025) "Generation of hydrogen and freshwater through a microgrid using internal combustion engines , micro gas turbines , and solar energy," in, pp. 1–9. Available at: https://doi.org/10.1088/1755-1315/1500/1/012087.

Ma, N. *et al.* (2024) "Large scale of green hydrogen storage: Opportunities and challenges," *International Journal of Hydrogen Energy*, 50, pp. 379–396. Available at: https://doi.org/10.1016/j.ijhydene.2023.09.021.

Martínez de León, C. *et al.* (2024) "Levelized Cost of Storage (LCOS) for a hydrogen system," *International Journal of Hydrogen Energy*, 52, pp. 1274–1284. Available at: https://doi.org/10.1016/j.ijhydene.2023.07.239.

MathWorks (2025) "MATLAB and Statistics Toolbox Release 2025a, The MathWorks, Inc., Natick, Massachusetts, United States." Available at: www.mathworks.com.

Ministry of Energy of Chile (2020) *National green hydrogen strategy. Chile, a clean energy provider for a carbon neutral planet*.

Ministry of Energy of Chile (2025) "Solar Explorer." Available at: http://solar.minenergia.cl/inicio.

Moran, C. *et al.* (2024) "The hydrogen storage challenge: Does storage method and size affect the cost and operational flexibility of hydrogen supply chains?," *International Journal of Hydrogen Energy*, 52, pp. 1090–1100. Available at: https://doi.org/10.1016/j.ijhydene.2023.06.269.

National Renewable Energy Laboratory (NREL) (2024) "System Advisor Model (SAM)." Available at: https://sam.nrel.gov/.

Olabi, A.G. *et al.* (2023) "Green hydrogen: Pathways, roadmap, and role in achieving sustainable development goals," *Process Safety and Environmental Protection*, 177(December 2022), pp. 664–687. Available at: https://doi.org/10.1016/j.psep.2023.06.069.

de Oliveira Junior, S. (2013) *Exergy*. London: Springer London (Green Energy and Technology). Available at: https://doi.org/10.1007/978-1-4471-4165-5.

Zhang, T. *et al.* (2023) "Hydrogen liquefaction and storage: Recent progress and perspectives," *Renewable and Sustainable Energy Reviews*, 176(January), p. 113204. Available at: https://doi.org/10.1016/j.rser.2023.113204.