Techno-Economic Analysis for Co-located Solar and Hydrogen Plants

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***Abstract*—Power-to-X technologies with flexible electricity consumption has the potential improve the utilization of variable power generation. Both concentrated solar power (CSP) and photovoltaic (PV) plants can be used to produce green hydrogen, utilizing high temperature electrolyzers (HTE) or low temperature electrolyzers (LTE), respectively. There have been limited studies examining the feasibility of co-locating solar and hydrogen plants from a techno-economic standpoint. This paper presents a detailed analysis and optimization to compare the economic feasibility of an integrated CSP and HTE system versus an integrated PV and LTE system. It is assumed that the steam generated by the CSP is solely directed towards HTE, while the electricity produced by the PV system is either supplied to the grid or directed towards the LTE system. The Renewable Energy Integration & Optimization (REopt) and System Advisor Model (SAM) frameworks developed by the National Renewable Energy Laboratory (NREL) are adopted and modified to perform the analysis. The results of the case study indicate that the integrated CSP and HTE system is more economically feasible compared to the integrated PV and LTE system, mainly due to the lower cost of thermal energy storage.**

***Index Terms*—hydrogen, concentrated solar power (CSP), photovoltaic (PV), techno-economic analysis (TEA)**

I. Introduction

Solar energy is playing a major role in the energy revolution due to its low cost and very large resource potential. According to the International Energy Agency (IEA), global solar PV generation has reached approximately 1,002.9 TWh in 2021 [1]. As of 2021, the installed capacity of CSP has grown to 6.8 GW globally, which is almost 20 times greater than the 354 MW capacity recorded in 2005. [2]. However, solar power suffers from high temporal variability which is an impediment especially at high energy shares. Since electricity is expensive to store directly, other energy carriers like hydrogen and its derivatives could play a key role in tackling the uncertainty and variability of solar energy, and help to accommodate higher shares of solar energy in the power system. Meanwhile, hydrogen holds a potential as a means to reduce emissions in sectors that have been proven challenging to decarbonize, such as the industrial and transportation sectors. Thus, the integration of solar (CSP or PV) with hydrogen production is gaining increasing attention as a means to improve energy security, reduce greenhouse gas emissions, and promote sustainable development. However, the economic and technical challenges of implementing such co-located solar and hydrogen plants have rarely been analyzed in depth, which is crucial for evaluating their viability and competitiveness [3].

A. Literature Review

Solar energy harvesting refers to the process of capturing and converting the sun's energy into usable forms such as electricity, heat, or light. This is achieved through the use of PV panels or solar thermal systems like CSP that transform solar radiation into direct current (DC) electricity or thermal energy. Opportunities for solar energy harvesting have received significant attention in recent years. Main research topics in solar energy include: material innovations, such as the selection of heat transfer fluid in CSP [4] and the development of PV cell materials [5]; the improvement of power generation efficiency, such as solar tracking systems [6] and solar farm layout design [7]; grid integration of the solar energy, such as solar forecasting [8]–[10]; the efficient integration of energy sources, such as energy storage [11] or power-to-X.

Hydrogen has been an important industrial feedstock for decades and can be produced from various sources such as natural gas, coal, water, and biomass [12]. Currently the main method of hydrogen production in industry is steam methane reforming [13], which results in significant greenhouse gas emissions. Other methods of hydrogen production include water electrolysis, coal gasification, and biomass gasification [14]. The increasing demand for clean energy and the initiatives in industrial decarbonization have led to a growing interest in green hydrogen production [15].

The integration of solar and hydrogen plants offers several benefits such as maximizing the utilization of renewable energy sources, reducing the generation variability, and reducing overall system costs. Solar-hydrogen technologies can potentially help decarbonize various sectors by providing clean hydrogen fuels [15], [16].

Although there is a growing interest in integrated energy systems, there have been limited techno-economic analysis (TEA) studies to evaluate the economic viability of integrated solar and hydrogen systems. TEA can assess the feasibility and competitiveness of the energy mix and provide valuable insights into the technical and economic trade-offs involved in integrating CSP or PV with hydrogen production, as well as the impact of various design and operating parameters on the performance and costs of the hybrid system.

B. Research Objectives

This study aims to conduct a comprehensive TEA of co-located solar and hydrogen plants, and compare the economic viability of CSP & HTE versus PV & LTE. These findings could help inform decision-makers and policy-makers in energy system planning. The study leverages the Renewable Energy Integration & Optimization (REopt) and System Advisor Model (SAM) tools developed by the National Renewable Energy Laboratory (NREL) to model the two types of solar plants and electrolyzers, and evaluate the impact of various economic parameters on the hybrid plant's performance and costs. A sensitivity analysis is performed to explore the impact of hydrogen prices on the integrated energy system configuration.

The rest of the paper is structured as follows: Section II outlines the techno-economic methodology used in this study; Section III shows the results of the case studies with various combinations of integrated energy system (IES) components; and Section IV concludes the paper and highlights potential future directions of research.

II. Methodology

The optimization for the solar-hydrogen energy system and PV modeling are performed by adopting REopt [17], which considers site-specific factors such as weather conditions, electrical demand, and energy market prices to optimize the economic benefits for end-users by determining the capacity and operational decisions of system components. The overall framework of the REopt optimization for the integrated energy system has been shown in our previous study [3]. Additionally, the heliostat layout and tower dimension are optimized based on the weather condition and location of the site. The modeling and simulation of CSP were performed using SAM [18], which assesses the performance and economics of renewable energy technologies. The weather data is retrieved from the National Solar Radiation Database (NSRDB) [19]. Pysam, which is a python package developed by the SAM team, is used as a bridge to connect REopt and SAM, which allows modeling, simulation, and optimization for a particular site simultaneously. Figure 1 provides an overall architecture of the REopt modules adopted/created in this study, along with their input and output parameters and constraints.

For modeling hydrogen production, the LTE technology takes electricity and a feedstock (e.g., water) to produce hydrogen. The user-inputs to REopt for the electrolyzer include the capital and operation and maintenance (O&M) costs, feedstock, electric energy consumed to hydrogen produced ratio, hydrogen sale price, etc. The modeling of HTE takes into account an important parameter, namely the ratio of thermal energy consumed to hydrogen produced, in addition to the electricity consumption rate. It is assumed that all the heat required by the HTE comes from the CSP, and the electrical energy required by the HTE is also converted into heat to be supplied by CSP. Since by default all the thermal energy generated by the CSP is used to supply the HTE, a certain amount of parasitic load needs to be considered in the CSP model to maintain both the flow of the molten salt and the molten salt state when there is no sunlight. Figure 2 depicts the concept of the co-located CSP and HTE system. A number of financial parameters such as tax rates, investment-based incentives, capital-based incentives, production-based incentives, discount rate, and modified accelerated cost recovery system (MACRS) are also taken into account to obtain the most realistic results.

In order to comprehensively perform the TEA of hybrid solar and hydrogen systems under different conditions, three distinct scenarios are designed and compared, considering factors such as constant or variable eletrolyzer power and fluctuating electricity and hydrogen prices.

- **Case I: CSP with constant power electrolyzer**: This case assumes a constant HTE production rate, which is independent of weather conditions or insolation levels. The optimal sizes of the electrolyzer and thermal energy storage (TES), and energy dispatch plan will be determined.
- **Case II: CSP with variable power electrolyzer**: A variable HTE production rate is assumed in this case. The amount of energy generated will vary depending on weather conditions, to reflect real-world performance. The optimal sizes of the electrolyzer and thermal energy storage (TES), and energy dispatch plan will be determined.
- **Case III: PV with variable power electrolyzer**: In the first two CSP cases, TES can smooth out solar fluctuations for HTE operation. In this case, only the variable power electrolyzer is considered, since battery storage system would not be cost-effective in a system with a potential downstream hydrogen storage. Furthermore, LTEs are more adaptable to fluctuating operating conditions than HTEs.

The hybrid system modeling considers factors such as energy balance, storage state, capacity, net import/export, and peak demand, to minimize the system cost. The optimization considers installation and O&M costs, electricity purchase, taxes/incentives, and hydrogen sales. REopt's architecture and parameters are depicted in Fig. 1. The mixed-integer linear programming solver in FICO Xpress is used to determine the optimal component selection, sizing, and dispatch. Results include component sizes, system expenditure, levelized cost of hydrogen (LCOH), levelized cost of energy (LCOE), payback period, life cycle cost, and net present value. These results provide useful information for IES investment, planning, and operation. The reference for the mathematical formulations is available in [21].

III. Numerical Experiments

The weather data is collected at a location with abundant solar resource (30.9878° N, 102.2683° W) in Texas of the United States. The wholesale market prices from the Electric Reliability Council of Texas (ERCOT) in year 2019 are used to calculate the costs of CSP parasitic load, and the price data can be found in our previous study [3]. For the PV

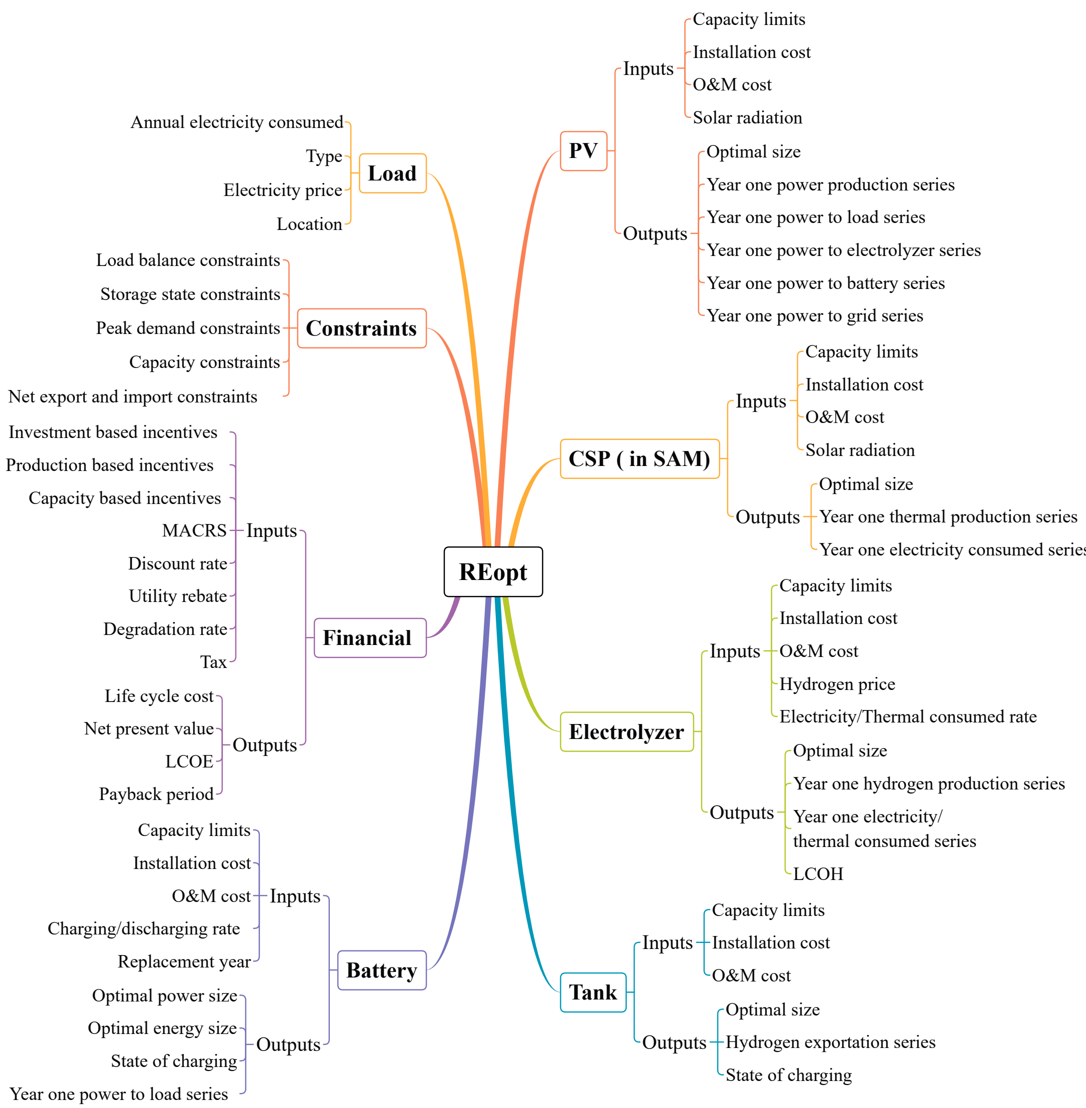

Fig. 1: Model architecture of the REopt modules adopted/created in this study

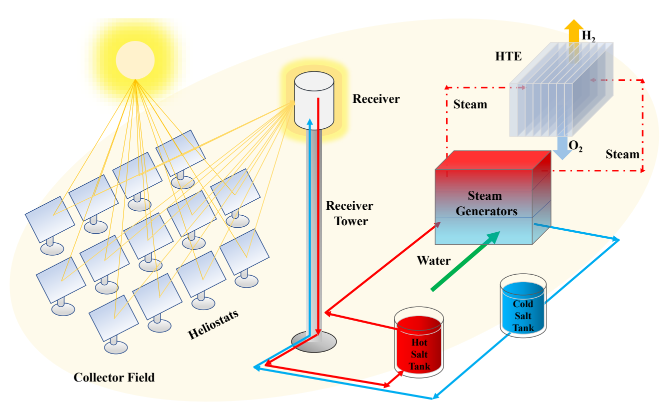

Fig. 2: Co-located CSP and HTE systems, including main subsystems like solar field, receiver, steam generators, HTE and TES subsystems (modified from [20]).

system, it is assumed that no extra local load is served by the system. Figure 3 depicts the ambient temperature and direct normal irradiation (DNI), which have significant impacts on the energy production of the IES. Other key assumptions for the IES setup are summarized in Table I [18], [21], [22]. The planning horizon for the IES is 25 years, and the 8,760 hourly data of the modeled year (2019) is input to REopt to analyze the full planning period. A constant rate of change in future grid electricity and O&M costs is assumed to account for projected cost escalation (or de-escalation) rates when discounting factors are included. Furthermore, the uncertainties in future predictions of weather and H_2 load are not considered in the study. All costs and benefits are discounted with a specified discount rate to present values using standard economic functions. For the capital and operating costs of the CSP, PV, TES, different hydrogen generation technologies, and others, the NREL's Annual Technology Baseline (ATB) [23] is adopted as a reference.

TABLE I: Key assumptions in the integrated energy system setup.

Parameter	Value
Hydrogen sale price	\$2.8/kg
LTE energy consumed per kg of H_2	55 kWh/kg
HTE energy consumed per kg of H_2	48 kWh/kg [a]
System capacity	115 MW [b]
CSP installation cost	\$6516/kW
CSP O&M cost	\$66/kW
Electrolyzer installation cost	\$48,000/kg/hr
Fixed electrolyzer O&M cost	\$3,600/kg/hr
Variable electrolyzer O&M cost	\$0.24/kg
Planning period	25 years
Steam temperature	575°C
Input water temperature	27°C
Steam pressure	10 atm
Parasitic load of CSP	632.5 kW
Steam storage installation cost	\$20.24/gal

[a] (48 kWh/kg): Net energy rate. The real gross thermal energy consumption rate used in this paper is 62.5 kWh/kg.
[b] (115 MW): In this paper, the capacity of the system is predefined. For the CSP case: the heliostat, tower, and receiver configuration for a 115 MW CSP electricity generation system is adopted, so the thermal energy generated from this configuration is greater than 115 MW.

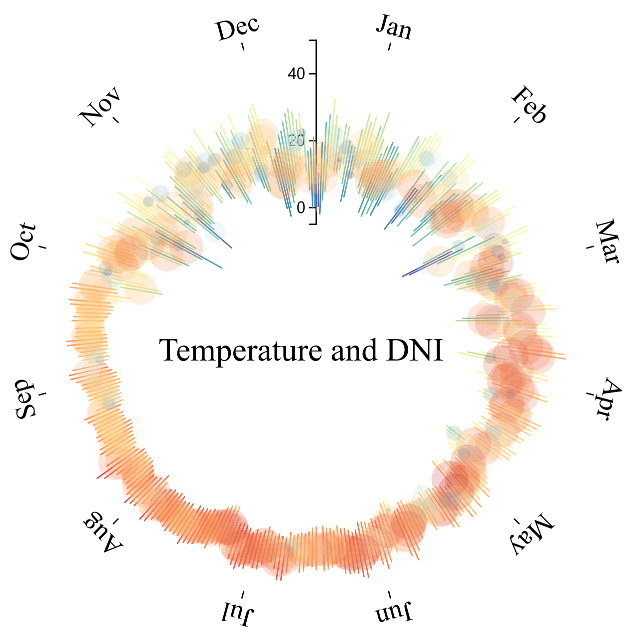

Fig. 3: Temperature and DNI at the chosen site throughout the year. The size and color of the bubbles represent the intensity of the solar radiation; a bigger size indicates stronger solar radiation. The color of the lines represents the temperature, with blue for low temperatures and orange for high temperatures.

A. Results and Discussion

Table II summarizes the optimal sizing of components, total system costs, energy efficiency, LCOE, and LCOH for the three cases. The results indicate that Case I (CSP with constant power electrolyzer) has the highest total system cost and LCOH, despite having the smallest size of electrolyzer. The system can support electrolyzer operations up to 3,380 kg/h, but the size of the electrolyzer is limited, resulting in a large amount of heat being curtailed and the energy efficiency being only 8.18%. Case III (PV with variable power electrolyzer) has the lowest system cost, but also the lowest energy efficiency. Figure 4 illustrates the generation stack for 350 hours to balance the electrolyzer load in the three cases. In Case I, the TES is used to maintain stable operation of the HTE, while Case II allows for a larger HTE to be installed to maximize the solar energy utilization. Case III includes an LTE for daytime operation, but the optimal LTE size limits the use of solar energy, leading to reduced efficiency and increased LCOH compared to other cases.

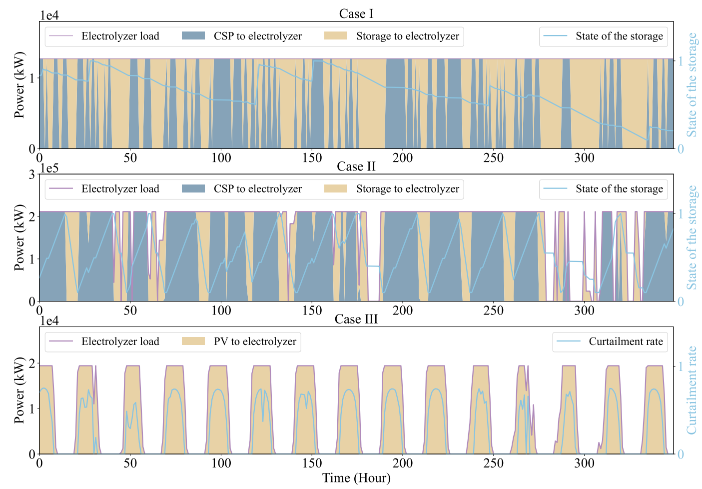

Fig. 4: Electrolyzer load balance of the three cases from different components. The right vertical axis of the first two graphs represents the charging state of the thermal energy storage system, and the right vertical axis of the last graph represents the curtailment rate of the PV system.

TABLE II: Key results of the integrated energy system analysis

Technology	Case I	Case II	Case III
LCOH (\$/kg)	9.324	1.313	6.297
LCOE of solar (\$/kWh)	N/A	N/A	0.064
Storage capacity (MWh)	32.226	13.260	N/A
Electrolyzer (kg/h)	203.63	3,383.162	358.762
Total system cost (\$)	367,959,076	124,921,295	114,390,208
Energy efficiency	8.18%	95.69%	5.165%
H_2 production per year (kg)	1,783,801	20,872,608	1,280,278

B. Sensitivity Analysis

A sensitivity analysis is conducted on Case III to further examine the impact of hydrogen selling price on the system configuration. Figure 5 shows the effect of the hydrogen price on different metrics of the system. As the hydrogen price increases, the optimal size of the electrolyzer will increase and consequently increasing the solar energy utilization rate also increase. This in turn leads to increased hydrogen yield and decreased total system cost. However, the LCOH of the system also rises due to the increased electrolyzer size that may not be fully utilized because of the volatility in solar generation. Thus, it is crucial to balance the size of the electrolyzer, the utilization of solar energy, and the cost of hydrogen production in the IES design, in order to achieve optimal efficiency and cost effectiveness.

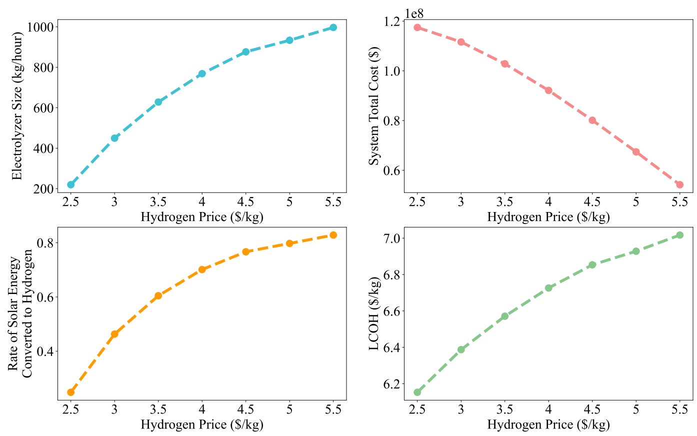

Fig. 5: For Case III (PV with variable power LTE): as the price of hydrogen increases, the optimal size of the electrolyzer grows in order to increase H2 production. At the same time, the utilisation rate of the solar energy also increases, with a corresponding decrease in the total cost of the system due to the increase in hydrogen yield. However as a result, the LCOH also increases, since the increased size of the electrolyzer is not fully utilised due to the volatility of the input energy.

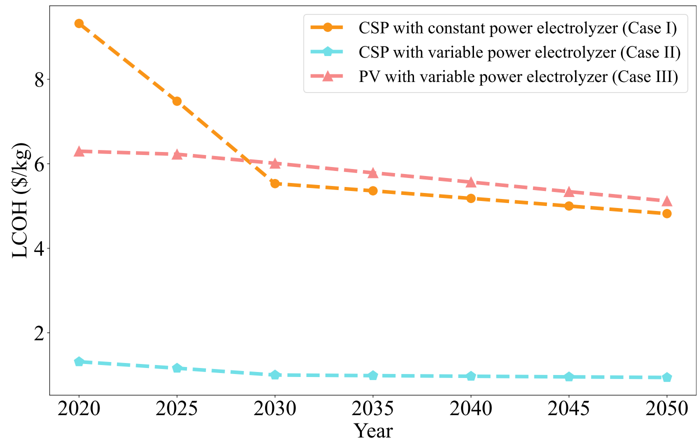

Fig. 6: As the technology matures, the installation and O&M costs continue to decrease, resulting in a lower LCOH. Case II (CSP with variable power electrolyzer) consistently has the lowest LCOH, and the Case I (CSP with constant power electrolyzer) LCOH is expected to be lower than the Case III (PV with variable power electrolyzer) LCOH after 2028.

TABLE III: Annual Technology Baseline ($/kW) [23]

Year	**CSP CAPEX**	**CSP O&M**	**PV CAPEX**	**PV O&M**	**Battery CAPEX**	**Battery O&M**
2020	4736	62.7	1600	16	840	410
2025	3599	53.7	1579	15	838	400
2030	2491	39	1482	14	620	340
2035	2366	39	1380	13	512	328
2040	2243	39	1279	12	454	313
2045	2118	39	1177	11	410	300
2050	1994	39	1076	10	346	289

In order to explore the impact of future technological developments leading to price changes on the economics of the IES, an additional sensitivity analysis is implemented. As with many technologies, the cost of CSP and electrolyzer systems are expected to decrease as the technology matures. Table III lists the ATB price adopted in this sensitivity analysis [23]. As shown in Fig. 6, the decreasing installed and O&M costs of these systems will result in a lower LCOH for the IES. In particular, Case II consistently shows the lowest LCOH due to its ability to optimally size the system components and maximize the solar energy utilization. On the other hand, Case I is also expected to have a lower LCOH than Case III after 2028, as the technology advances and becomes more efficient in managing the input energy volatility.

IV. Conclusion

This paper performed a techno-economic analysis of integrated solar and hydrogen systems (i.e., CSP with HTE, and PV with LTE). It is found from the case study that the integrated CSP and HTE system is more economically viable than the integrated PV and LTE system due to the low thermal energy storage cost. The study recommends carefully balancing the size of the electrolyzer, the utilization of solar energy, and the cost of hydrogen production in IES design, to achieve optimal efficiency and cost-effectiveness. From the sensitivity analysis, we find that the price of the technology has a significant impact on the LCOH. These findings could provide valuable insights for policy makers and energy producers in advancing the deployment of integrated solar and hydrogen systems.

Future research is needed to further explore the impact of other factors such as energy market conditions and government incentives on the economic viability of integrated solar and hydrogen systems. For example, the hydrogen tank can be used as an option in view of the demand in the hydrogen market.

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